PB-240 581

AIR POLLUTION: SYMPOSIUM ON LOW POLLUTION POWER SYSTEMS DEVELOPMENT HELD IN ANN ARBOR, MICHIGAN, ON OCTOBER 14-19, 1973

NATO Committee on the Challenges of Modern Society

Prepared for:

Environmental Protection Agency

1973

DISTRIBUTED BY:

NTIS
National Technical Information Service
U. S. DEPARTMENT OF COMMERCE

BIBLIOGRAPHIC DATA SHEET

1. Report No.

2.

PB 240 581

4. Title and Subtitle
Air Pollution, Symposium on Low Pollution Power Systems Development

5. Report Date

6.

7. Author(s)

8. Performing Organization Rept. No. 32

9. Performing Organization Name and Address
NATO Committee on the Challenbe of Modern Society, 1110 Bruxelles,
Brussels, Belgium.

10. Project/Task/Work Unit No.

11. Contract/Grant No.

12. Sponsoring Organization Name and Address
Office of Air and Waste Management, Environmental Protection
Agency, Washington, D. C. 20460

13. Type of Report & Period Covered

14.

15. Supplementary Notes

16. Abstracts

17. Key Words and Document Analysis. 17a. Descriptors

- air pollution
- lead particulate measurement
- gas turbines
- Rankine power systems
- Stirling Cycle Engines
- Stratified charge engines
- diesel engines
- rotary engines
- electric cars
- alternate fuels
- hydrogen fuels

17b. Identifiers/Open-Ended Terms

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
US Department of Commerce
Springfield, VA. 22151

PRICES SUBJECT TO CHANGE

17c. COSATI Field/Group

18. Availability Statement
Available from NTIS

19. Security Class (This Report)
UNCLASSIFIED

20. Security Class (This Page
UNCLASSIFIED

21. No. of Pages 395

22. Price PC/MF 10.25/2.25

i

FORM NTIS-35 (REV. 10-73) ENDORSED BY ANSI AND UNESCO. THIS FORM MAY BE REPRODUCED USCOMM-DC 8265-P74

SYMPOSIUM ON LOW POLLUTION
POWER SYSTEMS DEVELOPMENT

("Symposium Pour La Mise Au Point
D'industries à Sable Degré De")

October 14-19, 1973
Mariott Inn
Ann Arbor, Michigan

NATO Document No. 32

Sponsored by:

The Office of Air and Water Programs
U.S. Environmental Protection Agency,
Under the auspices of the Air Pollution
Pilot Project of the NATO Committee On
The Challenges to Modern Society

PREFACE

The United States, in November, 1970, as part of the NATO/CCMS Air Pollution Pilot Study introduced the Low Pollution Power Systems Development (LPPSD) Program. This was in response to a recognized need for development of low pollution vehicles among the NATO allies. As a first result of this initiative, the First Symposium on LPPSD was held the following February in Eindhoven, the Netherlands. At this conference a Memorandum of Understanding was circulated by the United States among the assembled nations. This proposed multi-lateral agreement would become the framework for cooperation in LPPSD among auto-producing NATO countries in the future.

On November 14, 1972, at the CCMS Plenary meeting at NATO Headquarters in Brussels, six nations signed the Memorandum of Understanding. These nations were: The United Kingdom; France; Italy; Germany; the Netherlands; and the United States. The cooperation of two nonmember countries who have strong industrial interest in this field, Japan and Sweden, is currently under negotiation.

Provisions of this Memorandum call for: (1) direct information exchange; (2) technical symposia; and (3) collaborative projects. A more detailed review of the background and evolution of the LPPSD Program is given in Appendix B.

The U.S. input into the LPPSD information exchange comes from the Advanced Automotive Power Systems (AAPS) Program, which provides for Federally sponsored research and development to produce an unconventionally powered, low pollution automobile. To stimulate and promote the maximum rate of technical progress toward the country's clean air objectives, the Advanced Automotive Power Systems Development Division of the Environmental Protection Agency (EPA) holds periodic coordination and progress meetings with all of its contractors, staff, consultants, prospective contractors, and other interested parties. The meetings focus attention on the status of the programs and provide an opportunity for interaction between the participants on problem areas of mutual concern.

This report summarizes the presentations and discussions at the second LPPSD Symposium held on October 15-19, 1973, in Ann Arbor, Michigan. This symposium encompasses the regular AAPS contractors, coordination and progress meeting. It is the first official undertaking under the provisions of the Memorandum of Understanding. Documentation such as this is believed to be both an effective and timely means of providing a full and up-to-date accounting of LPPSD progress in the U.S. to its MOU counterparts. It is hoped that similar reporting schemes will be adopted by the other signatory countries as partial fulfillment of the terms of the agreement.

This document includes a short Executive Summary of the entire Symposium, a review of the status of each participating country as presented by their respective representatives in a panel session, and important elements of the technical presentations which covered the following subjects:

- Gas Turbines, their components and selected manufacturing processes
- Rankine power systems (four basic types) and components
- Stirling Cycle Engines
- Stratified Charge Engines
- Diesel Engines
- Rotary Engines
- Electric Cars
- Alternate Fuels
- Hydrogen Fuels
- Schemes for reducing fuel consumption
- Reduction and measurement of lead particulates

Each of these presentations is summarized along with the pertinent items of discussion. Wherever possible specific data, principle conclusions, and key illustrations are included.

A luncheon speech by Eric O. Stork, EPA, on Review of Conditions, Circumstances, and Evolution of Present Stringent Automobile Emission Standards is transcribed in Appendix C.

An important part of the Symposium was the hardware exhibits and displays. Six operating vehicles were available for attendees to drive and examine in addition to full-scale mock-ups. These are listed and illustrated in Appendix D.

Additional supplementary material contained in the appendices include a bibliography of AAPSD reports released through October, 1973, (Appendix E), a Status Report on the Health Hazards of Nickel Oxide (Appendix F) and a Summary of Exhaust Emission Tests and Standards (Appendix G).

TABLE OF CONTENTS

Page

TITLE PAGE

PREFACE 1

TABLE OF CONTENTS iv

EXECUTIVE SUMMARY by John H. Ludwig x-1

TECHNICAL SUMMARY 1

I. INTRODUCTORY SESSION 1

  A. Welcome - Mayor James E. Stephenson of Ann Arbor, Michigan 1
  B. Conference Remarks - Fitzhugh Green 1
  C. Conference Remarks - Professor Nimet Ozdas 4
  D. Keynote Address - Robert L. Sansom 6
  E. Overview of Low Pollution Power Systems Programs in Participating Countries 10

    1. United States - J. J. Brogan 10
    2. United Kingdom - G. Donald 11
    3. Sweden - O. Ljungstrom 11
    4. The Netherlands - J. G. Kuiperbak 12
    5. Italy - V. Opportuno 13
    6. Federal Republic of Germany - R. D. Dr. Dieter Hartmann 13
    7. France - C. Lamure 14

  F. Summary of Significant Comments Concerning Activities of the NATO/CCMS Initiative 15

II. STIRLING ENGINES 18

  A. Philips Research Laboratories - The Netherlands 18
  B. United Stirling - Sweden 34
  C. M.A.N. - Germany 56

III. GAS TURBINE ENGINES 62

  A. Gas Turbine Development Overview - George Thur, EPA, AAPS Division 62

Page

B. Volkswagen Gas Turbine Research........................ 60
C. Chrysler Baseline Gas Turbine Program - Review and Status........................ 76
D. NASA Component Support for Baseline Engine........................ 110
E. Solar Low Emission Burner for Baseline Gas Turbine........................ 115
F. AiResearch Integrated Control System for the Baseline Gas Turbine........................ 117
G. Pratt & Whitney Low Cost Turbine Wheel Manufacturing Development........................ 133
H. Owens-Illinois Oxide Recuperator Development........................ 151

IV. RANKINE ENGINES........................

A. Rankine System Development Overview - George Thur, EPA, AAPS Division........................ 159
B. Critical Component Development of Saab-Scania........................ 161
C. Water Base Reciprocating System Status - Scientific Energy Systems, Inc........................ 171
D. Organic Fluid Reciprocating System - Thermo Electron Inc. 179
E. Water Base Turbine System - Lear Motor Company........................ 184
F. Organic Fluid Turbine System - Aerojet Liquid Rocket Co. 194
G. California Clean Car Program........................ 200

V. STRATIFIED CHARGE ENGINES........................ 203

A. EPA Program........................ 203
B. TACOM Program........................ 204
C. Honda CVC Vehicle Tests by EPA........................ 209
D. Volkswagen Program........................ 214

VI. DIESEL ENGINES FOR LOW POLLUTION FROM AUTOMOBILES........................ 223

A. Presentation by Ricardo & Co. Engineers, Ltd........................ 223
B. Presentation by Vehicle Engineering Division, Department of Environment - London, England........................ 228
C. EPA Diesel Study Status........................ 233

Page

VII. ROTARY COMBUSTION ENGINES.. 236

A. General Status - University of Michigan................. 236

B. Rotary Engines in Sweden - Ljungstrom (Guest Presentation).. 239

VIII. ELECTRIC CAR AND ALTERNATIVE FUELS........................... 241

A. Impact Study of Electric Cars for Los Angeles - General Research Corp.. 241

B. Alternative Fuels - Institute of Gas Technology.......... 252

C. Alternative Fuels - Esso Research....................... 255

IX. HYDROGEN FUEL USAGE.. 268

A. Partial Injection - NASA Jet Propulsion Laboratory....... 268

B. Hydrogen Storage in Vehicles Using Metal Hydrides........ 277

X. REDUCING FUEL CONSUMPTION FOR CURRENT AUTOMOBILES........... 283

A. DOT Study by A. D. Little, Inc.......................... 283

B. DOT Study by Southwest Research Institute................ 288

C. EPA In-House Component Study............................ 290

D. EPA Fuel Economy Test Results........................... 295

E. Potential of Heat Pipe for Reduced Fuel Consumption and Low Pollution for Model Year 1973 and 1974.............. 301

XI. LEAD EMISSIONS... 308

A. Filter Systems to Remove Lead Particulates............... 308

B. On Line Monitoring of Lead Emissions.................... 308

APPENDIX A - List of Attendees and Representatives

APPENDIX B - Background and Evolution of CCMS/LPPSD Leading to the Signing of the Annex Agreement on the Memorandum of Understanding by the Government Representatives

APPENDIX C - "Review of Conditions, Circumstances, and Evolution of Present Stringent Automobile Emission Standards"

APPENDIX D - Hardware Exhibits

APPENDIX E - Bibliography of Alternative Automotive Power Systems Division - Annual, Final, and Summary Reports, October 1973

APPENDIX F - Status Report on Hazards of Nickel Oxide - October 12, 1973

APPENDIX G - Summary of Exhaust Emission Test Procedures and Standards

EXECUTIVE SUMMARY

Second Symposium on Low Pollution Power Systems Development

The Second Symposium on Low Pollution Power Systems Development (LPPSD), organized under the auspices of the Air Pollution Pilot Project of the NATO/CCMS, was held in Ann Arbor, Michigan, on October 14-19, 1973, in conjunction with the meeting sponsored by the U.S. Environmental Protection Agency to coordinate the efforts of contractors associated with EPA's program for development of alternative automotive power systems. Approximately 340 people attended the meeting, 37 as official delegates of the NATO/CCMS Symposium. Of the 340 total attendees, 54 were from countries other than the United States or represented foreign industrial groups.

Opening Session. The opening session of the Symposium commenced with greetings from Mr. James E. Stephenson, the Mayor of Ann Arbor, Michigan; remarks by Mr. Fitzhugh Green, Associate Administrator for International Activities of EPA, relating the Air Pollution Pilot Project of NATO/CCMS to other international activities of EPA; comments by Professor Nimet Ozdas, Assistant Secretary General for Scientific and Environmental Affairs, NATO, concerning the purposes of the NATO/CCMS program and the role played by the Air Pollution Pilot Project, particularly the significance of this Symposium to exchange information on the development of low pollution automobile power systems as an effort to assist the international community in solving one of society's major problems; and a Keynote address by Mr. Eric O. Stork, Deputy Assistant Administrator for Mobile Source Air Pollution Control, EPA, outlining the issues confronting the international community with regard to the need for control of vehicle emissions.

Following these introductory presentations, each member of a panel, composed of delegates from the Federal Republic of Germany, France, Italy, the Netherlands, Sweden, United Kingdom, and the United States, reviewed the rationale in his country for motor vehicle pollution emissions control and activities in the development of low pollution power sources. These presentations were followed by general discussions by all in attendance.

Significant comments concerning the activities of the NATO/CCMS initiative, resulting both from the introductory remarks, the presentations by the panelists, and the discussion following the panel presentations, concerned the need for the NATO/CCMS program to broaden its perspective beyond the technical and related economic aspects of engine system development to include problems related to energy conservation, noise suppression, and vehicle safety. It was suggested that NATO/CCMS might desire to address itself to studies looking toward the need for an approach integrating all of these aspects and relating these to the totality of society's needs.

The need for technology assessment within the NATO/CCMS LPPSD program was suggested as a means to better focus on the problems associated with future cooperative activities and thus allow a more meaningful comparison of alternative approaches by different countries. Specifically, it was suggested that the NATO/CCMS group give consideration to joint determination of a set of criteria for this purpose, such criteria to include all pertinent factors such as weight of vehicle, fuel consumption, maintenance, reliability, cost, users assessment, etc.

The possibility of effects of automotive emissions, combined with other sources of pollution, on global climate resulting in irreversible ecological effects was posed as a serious question needing resolution in order to evaluate the total international effort, as well as each country's individual effort, to control motor vehicle pollution.

An evaluation of the total international effort in research and development on low pollution power systems, compared to the projected annual economic penalties estimated as needed to meet motor vehicle emission standards, was posed as a necessary input item to determine the magnitude of the economic gains to be expected from research development activities. Such information on an international basis would be helpful to assess the viability of the NATO/CCMS initiative and the need for possible further development of the program.

The opening morning session closed with the suggestion by the chairman that each of these issues needed resolution and that the NATO/CCMS group might well consider including them in the development of its future program.

Stirling Session. The session on Stirling cycle engine development consisted of four presentations relating current European activities in this area and indicating that the Stirling cycle engine offers a viable alternative for both bus and automobile application. Research results presented indicated low emissions, high efficiency, and low noise and vibration. Emissions of exhaust hydrocarbon and carbon monoxide are below the 1976 standards of the U.S. without the use of auxiliary control devices, and for nitrogen oxides the 1977 U.S. standards can be met by utilizing exhaust gas recirculation which, for the Stirling engine, does not result in a loss of power output. Noise problems are associated with tires and auxiliary equipment rather than from the engine itself. High efficiencies are attainable for both part and full load, and multi-fuel capabilities add to the attractiveness from the point-of-view of fuel conservation. Remaining research and development is required on various components to improve reliability and endurance and reduce cost. Since European experience in Stirling cycle engines is in an advanced stage of development, the presentations under the auspices of NATO/CCMS at the Symposium were particularly pertinent and well received.

Gas Turbine Session. Of the eight presentations concerning the development of gas turbine engine systems and components, only one was from a European organization, reflecting the longer period of interest and effort in this type of advanced power system in America as compared to Europe and the support by the Environmental Protection Agency in the U.S. as one of the major program areas in their Alternative Automotive Power Systems Program.

Progress has been made over the past year to overcome some of the major drawbacks in the utilization of the turbine as a automotive power system through effort in development of critical components and their integration into more versatile power systems. However, additional major improvements still remain, e.g., improved fuel economy, reduced emissions, and reduced production costs. All of these areas are under investigation and progress was reported during the morning session on systems integration and during the afternoon on solutions to component problems including consideration of cost reduction.

The area of improved fuel economy is being attacked through several approaches, such as improved components, higher temperature operation, variable turbine inlet guides and water injection. It is estimated that improvements in fuel economy of up to 50 percent may be achievable which, if ultimately realized, would make fuel consumption for the turbine, generally comparable to internal combustion engine power systems.

Problems still remain in attaining the U.S. 1976-77 standards for emissions, particularly for NO_x; however, research is underway on improved combustors to meet the 1976-77 emission requirements, and results to indicate that the requirements are met for a narrow range of operating conditions with the expectation that further reductions are attainable.

Although there is still much effort required to overcome the present shortcomings to produce a viable competitive turbine engine, the chances for success, although limited, are not considered to be entirely unattainable.

Rankine Systems Session. Recent research and development activities, both in the U.S. and in Europe, reported during the meeting indicated that great progress has been made in solving many of the problem areas of concern only several years ago. Although many technical and economic problems remain before Rankine cycle engine systems are competitive with existing internal combustion engine systems, the gap is closing rapidly. Extensive research and development on the major components was reported for water-based systems incorporating both reciprocating and turbine expanders and similarly for organic fluid reciprocating and turbine expanders. Six papers were presented, one of which reported on activities in Sweden.

There was general agreement that the U.S. standards for 1976-77 can be met for the external combustors used in Rankine systems and the component development indicated no problems regarding system configurations that would allow installation in current automobiles. Much work still remains, however, to remove remaining technical problems, which appears to be resolvable, and to, more importantly, optimized components to improve fuel economy. Presently reported prototype systems show promise of approaching fuel consumption values comparable to internal combustion engine systems modified to meet the 1976-77 U.S. standards, and their is some promise and optimism that fuel consumption values will improve even more as work continues. No firm data were reported on the question of cost for the Rankine powered vehicle as compared to a conventional ICE automobile; this area remains for future determination.

Electric Car and Alternative Fuels Session. Brief status reports were made for two studies that had been underway for only a short time; hence the reports covered only statements of objectives and procedures to be used. One of these is a study to evaluate the impact of battery-electric cars on electric power demand and air quality in the Los Angeles region and the impact nationwide on energy resources. The other is a feasibility study of alternative fuels for automotive uses considering projected future demands for fuel to operate vehicles in various types of power systems and fuels derived from a multiplicity of energy sources. Initial screening of both vehicle power source utilization and energy sources indicates that gasoline and distillate from oil shale or coal and methanol from coal offer the most promising opportunities. An additional output from the study will be definition of research and development needs.

Special Luncheon for NATO/CCMS Delegates. Mr. Eric O. Stork, Deputy Assistant Administrator for Mobile Source Pollution Control, EPA, as guest speaker at the luncheon, reviewed the history of legislative and administrative activities in the United States regarding the promulgation of the 1975-76 vehicle emission standards in the U.S. by the Congress and subsequent decisions by the Administrator of EPA and a Federal Court in postponement of these standards until 1976-77. The review was very well received by the group in that it clarified much of the confusion concerning the background of these standards in relation to EPA's Alternative Automotive Power Systems Program.

Stratified Charge Session. Four reports on continuing developments in the stratified charge (nonhomogeneous fuel charge) internal combustion engine indicated this power system as one of the leading alternatives to replace the present internal combustion engine. Because stratified charging allows the use of leaner air/fuel mixtures using a range of fuels, the system offers overall good economy and lower emissions than conventional engines. However, auxiliary equipment and changes in engine operation characteristics are still necessary to meet the 1976-77 U.S. emission standards, e.g. catalytic reactors to further reduce HC and CO levels to meet the standards, exhaust gas recirculation for NO_x control, and throttling of intake air under part load operation. Even though emission controls exact considerable penalty in fuel consumption, the economy of the modified system is still good as compared to the conventional engine modified to meet the 1976-77 standards.

Hydrogen Fuel Investigations. Considerable interest was expressed in a new concept presented, the principle of which is the generation by the power system of sufficient hydrogen to use with conventional gasoline fuel to allow utilization of lean mixtures sufficient to overcome the NO_x problem. This low cost system, which is only in the early stages of an investigation that will continue for another two years, shows potential for meeting the 1977 NO_x standards even though present studies indicate that hydrocarbon emissions are considerably higher than the 1976 U.S. standards for the combustion system unmodified for emission control. Fuel economy is comparable to present ICE power systems. Although extensive development work is required to resolve problems concerning the hydrogen generator (e.g., reduction or elimination of water) and the integration of the hydrogen-gasoline fuel system into the standard internal combustion engine, the general reaction of the meeting was that the concept deserved thorough exploration of its possibilities.

In another study, progress was reported on the storage of hydrogen for use as an automotive fuel utilizing metal hydrides, such storage to allow use of hydrogen without the hazards presented by presently available containers in motor vehicle application.

Rotary Engine. The single paper reviewing the status of the rotary combustion engine illicited considerable discussion from the floor, probably indicating the extensive work underway worldwide on engine systems of this type. Although the engine offers several advantages for automotive application such as low size and weight, simplicity, and a number of desirable operating characteristics, serious problems still remain such as poor fuel economy due principally to leakage past the engine seals. Cost is a major question because new manufacturing technology is required. Regarding pollutant emissions, hydrocarbons are higher than for a conventional engine but the NO_x emissions are lower. Emission control techniques applicable to the rotary engine are essentially the same after-engine treatment utilized for conventional engines.

Fuel Economy. Progress reports were presented on a number of studies underway looking into possibilities for improving the economy of vehicle operation by reducing fuel consumption. Some studies of course relate to the increasing critical nature of future energy resources, and will examine a number of variables including vehicle design parameters, fuels, and operating factors such as durability, reliability, and maintenance. In closing the session, the rationale for an analysis of results of EPA's fuel economy tests based on 1973 and 1974 model-year certification testing was presented.

Diesels for Automotive Use. Data presented in three papers, two of which were by European organizations, confirmed previous information that HC and CO emissions from a diesel powered automobile could meet the U.S. 1976-77 standards and the NO_x emissions could probably be reduced to meet the U.S. 1977 standards using exhaust gas recirculation. Also there was no question that fuel economy would be greater for the diesel powered vehicle as compared to the ICE powered vehicle.

However, the question of customer acceptance due to higher first cost, lower power ratio and noise are still unresolved. In addition, questions on odor, smoke emissions, chemical composition and size of particulate (e.g., sulfates and organic compounds of possible health hazards) were raised as areas needing further clarification.

Several recently initiated paper studies were reported, the purpose of which are to attempt to resolve these questions.

Lead Exhaust Filters. Investigations in England on the testing of an exhaust filter to remove lead originating in alkyl lead fuel additives were presented. The use of such filters is being considered as an interim measure pending investigation of possibilities for longer range technological changes. Preliminary results indicate an overall 50 percent efficiency with a fuel penalty of roughly 4 percent. Analytical studies are incorporated as a part of the program indicating that trapped lead is predominantly in the form of lead sulfate. Both road load tests and simulated laboratory tests are being carried out.

Heat Pipe. A report on development of a heat pipe in England to allow production of improved mixture homogeneity in gasoline fueled vehicles indicated that greater power and leaner mixture operation lead to possibilities of improved fuel economy. Technical problems involved and possible solutions were reported. Discussion from the floor raised questions concerning power losses leading to degraded performance during lean mixture operation. Results reported indicated large reductions in CO as compared to standard carburetion; however, HC and NO_x emission reductions were still large compared to the U.S. 1976-77 standards.

Government Representatives Meeting: Several subjects were considered by NATO/CCMS delegates at a meeting convened on Friday afternoon, October 19, 1973, after the close of the technical sessions as follows:

1. Discussion of knowledge development versus cost, advancing from basic to applied research and thence through various stages of development and culminating in product development. The focus of the discussion was on the efficacy of limited government funding in the knowledge-cost process and the opportunities open to all countries in the LPPSD agreement to optimize contributions by cooperation during research and early development stages.

2. Discussion of the merit of additional symposia. It was agreed that the First Symposium was an outstanding example of international cooperation on exchange of technical information on a timely basis, and it was unanimously expressed that additional symposia should be held annually in accord with the MOU.

3. Discussion of the need to include factors other than emissions control in future symposia, these to include noise and safety as well as fuel conservation, which has already been incorporated to a large degree into most governmental programs. It was recommended that consideration be given to combining symposia of the LPPSD with the similar symposia sponsored by the Experimental Safety Vehicle (ESV) program of the NATO/CCMS. Since the criticality of energy conservation has increased since the ESV and LPPSD programs were initiated, it was suggested that this factor might be salutary in bringing the diverging vehicle weight requirements of safety and fuel consumption into better harmony. As a consequence of this discussion, the U.S., as Pilot Country in the LPPSD initiative, will explore the possibility of joint symposia with the ESV program.

4. Discussion of the need to enumerate criteria which would allow more effective cooperation and comparison of results of work done in various countries. It was agreed that, rather than attempt to develop and agree to a set of criteria that would be used by all countries contributing to the LPPSD agreement, it would be desirable to delineate all of the areas of significance to the development of low pollution power systems, these to include the full range of conditions reflecting need and interest in various countries. Further, it was agreed that the U.S. would develop an initial paper for circulation to each delegate for his comments and additions and consideration of the merit of proceeding further, e.g., convening a meeting of a working group to further develop a set of criteria.

Upon completion of these discussions, final comments were made on the text of the Annex to the Memorandum of Understanding for the Low Pollution Power Systems Development Program. The meeting closed with agreement on the Annex by all countries followed by the signing ceremony. (The Memorandum of Understanding and the Annex are attached.)

Memorandum of Understanding on the Development of Low Pollution Power Systems for Motor Vehicles

1. This multilateral Memorandum of Understanding is concluded, following an exchange of views which took place within the Committee on the Challenges of Modern Society of the North Atlantic Council, between the following agencies.

   a. The Federal Ministry of the Interior of the Federal Republic of Germany;
   b. The Institute of Transport Research of France;
   c. The Ministry of Transport of Italy;
   d. The Road Transportation Service of the Netherlands;
   e. The Department of the Environment of the United Kingdom;
   f. The Environmental Protection Agency of the United States of America;

   The aim of this Memorandum is to encourage the development and testing of low pollution power systems for motor vehicles (which encompass new types of engines or advanced control systems for the internal combustion engine) in the interest of the health and well being of our peoples. The signatories to this Memorandum of Understanding will cooperate freely with each other and with other countries and international organizations with similar goals and programs so as to ensure that the total resourses available internationally for developing and bringing into use vehicles with low pollution power systems are deployed to the best advantage.

2. There are, in the countries of the signatories to this Memorandum of Understanding, governmental and/or industrially sponsored programs which collectively form a broad based attack on a challenging technological problem facing our society. Believing that international cooperation in the field of motor vehicle pollution control will prove fruitful for all, signatories will undertake a comprehensive exchange of knowledge gained about the design, the technical characteristics and the performance of low pollution power systems in the course of the conduct and monitoring of development

activities within their respective countries, insofar as such information is at their disposal for publication, in as timely and detailed a manner as is possible under their respective statutes. Additionally they will participate in technical symposia, expected to be held at least annually, for the review of research and development programs, discussions and exchange of information and ideas.

3. When two or more parties to this Memorandum of Understanding wish to develop more specific relationships on subprograms or projects within the fields of this Memorandum of Understanding, details of any agreement, arrangement or accord between them may be annexed to this Memorandum of Understanding.

4. The procedures to be used to implement this cooperative program will be developed among the signatories with the Environmental Protection Agency of the United States of America acting as the coordinating agency.

5. This Memorandum of Understanding is open to subsequent participation by the relevant governmental department or agency of other countries subject to the agreement of existing signatories.

6. This Memorandum of Understanding shall come into operation for each signatory on the date of its signature thereof and will remain in operation indifinitely in respect of all signatories which have not notified the termination of their participation by 30 days notice in writing.

Done November 14, 1972, at Brussels:

M. M. Frybourg, Directeur de l'Institute de Recherches sur les Transports (France)

Dr. Guenter Hartkopf, State Secretary, Ministry of the Interior (Germany)

Dr. C. Calenda, Ministre plenipotentiaire de lere classe (Italy)

Mr. J. G. Kuiperbak, Ministry of Transport (the Netherlands)

Sir Alan Cottrell, FRS, Chief Scientific Advisor to HM Government (United Kingdom)

Mr. R. W. Fri, Deputy Administrator, Environmental Protection Agency (United States)

DONE NOVEMBER 14, 1972 AT BRUSSELS:

UNITED STATES of AMERICA

FRANCE

FEDERAL REPUBLIC OF GERMANY

ITALY

THE NETHERLANDS

UNITED KINGDOM

Annex to Memorandum of Understanding on Low Pollution Power Systems Development Concerning Exchange of Technical Information

I. On November 14, 1972, a Memorandum of Understanding concerning Low Pollution Power Systems Development (LPPSD) was concluded between the appropriate agencies of the following nations: the Federal Republic of Germany, France, Italy, the Netherlands, the United Kingdom, and the United States, hereafter referred to as the "participants" to this agreement. This Memorandum included provisions for technical symposia, technical information exchange, and collaborative projects. This annex is designed to provide a timely, orderly, and efficient means of exchanging technical information on research, development, and testing of low polluting power systems among all of the participants in the Memorandum, so that each participant might keep abreast of parallel LPPSD developments in other countries party to the Memorandum.

II. Technical information on LPPSD shall be made available on a voluntary basis as described below:

(a) Any information made available under this annex will be made available simultaneously to all participants in the Memorandum by direct transmission to a contact to be named for each participant.

(b) Information exchanged may include (to the extent that the laws of the respective participants allow), but not be limited to:

1. General information of each participant's current LPPSD programmes, including their objectives, results, funding levels, etc.
2. Interim reports on LPPSD progress.
3. Final project reports.
4. Results of bilateral or multilateral collaborative projects undertaken under the Memorandum.
5. Reports issued as a result of technical symposia. In this regard the report on the annual LPPSD Conference will

constitute the annual report to the Committee on the Challenges of Modern Society on the progress made in LPPSD.

6. Other technical information likely to be of interest to the participants.

(c) Each participating state may provide information in its native language only.

(d) Proprietary information identified as such by the source shall be released only to those participants or persons specified by the source, or to whom release is subsequently authorized by the original source.

III. Any participant may terminate his participation in the program envisaged in this annex at any time by informing all remaining participants of his intention to do so.

IV. Changes may be made to this annex at any time subject to the approval by all participants.

V. This annex takes effect from the date of its signing by authorized representatives of all participants, and shall remain in operation indefinitely unless terminated with the consent of the participants.

DONE, OCTOBER 19, 1973, AT ANN ARBOR, MICHIGAN:

UNITED STATES of AMERICA

FRANCE

Hartmann

FEDERAL REPUBLIC OF GERMANY

ITALY

M.C. Kuiperbak

THE NETHERLANDS

UNITED KINGDOM

TECHNICAL SUMMARY

I. INTRODUCTORY SESSION

A. Welcome by James E. Stephenson, Major of Ann Arbor

In welcoming more than 500 attendees[*] from all over the world (54 from countries other than the U. S.), Mayor Stephenson noted the technological nature of Ann Arbor. It is the home of the University of Michigan and the research facilities of many major multi-national corporations -- an appropriate site for this Low Pollution Power Systems Development (LPPSD) Symposium.

B. Conference Remarks by Fitzhugh Green, Associate Administrator for International Activities, U. S. Environmental Protection Agency (EPA)

"I am representing Mr. Train, the Administrator of the Environmental Protection Agency. He has just been made head of our 10,000 person agency and he is very busy getting to know the Congress, working out some late changes to legislation, and getting to know the people around the country in our agency. He is very, very sorry that all of this is keeping him from being here this morning. He has been the head of the U. S. delegation to the CCMS for several years now. President Nixon has asked that, even though he has taken over a new job as head of EPA, he maintain the leadership of our representation in CCMS."

"I'd like to say a few words of background leading up to where we are today in terms of international activities in the field of the environment. In the first place, we are delighted with this particular kind of a meeting, because to us of EPA, it means that Government and industry are working together in a way that the scandal mongers can only be unhappy about. This is the kind of get-together on a common goal that is absolutely essential in all countries, if business and the governments of countries are to make the most of their respective centers of excellence, centers of power and centers of knowledge. Second, we've come a very long way in international activities in a terribly short time — not only in the rest of the world, but also a lot has been going on in our own country."

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[*] A list of the registered Attendees is given in Appendix A.

"When we started our agency less than three years ago, there were 15 different international programs going on. The great trick was to find out what these were all doing. That has now been accomplished. We also discovered that with the 6,000 people in our agency when we started and with the 10,000 people which we now have, there isn't anybody that doesn't want to be in international activities. We try to meet this interest by sending people abroad, by being sure that, when we have important and knowledgable visitors from other countries, have them meet the people in our laboratories, our regional centers, and our regional headquarters of which there are ten around the country. This interest goes on; and Mr. Train coming over to take care of us means that the interest in international activities is going to get stronger and stronger. He also brought over with him, on order from President Nixon, the leadership of our part of the USSR - US Bilateral activities."

"The reason EPA is so active in international affairs is two-fold. One, we realize full well, that, although we have some strengths in the field of environmental control understanding, we don't have all of the answers and we haven't done all of the research. The very fact that we have this meeting going on today indicates that there is a lot of research to be done and a lot of technology to be developed. So we are looking for answers to our own problems, and two, like the rest of you here, we are keen that not just a one country approach is made to the problems of the environment."

"I'll just cite briefly the increase in international activities that has occurred around the world in the last three years. These include: the CCMS activities with which you are very familiar; the great Stockholm Conference and 109 recommendations for national action which followed that; particularly, the agreement to go ahead on Earth Watch. Bob Frasch, head of programs down in Nairobe, was in this country the other day to begin talks with this and other nations about the details of putting together a world monitoring system. A program for information referral is also underway. It looks very much as if the United Nations Environment Program Fund will get underway. This involves the pledge of the member nations to provide a $100,000,000 which would be used as seed money to get environmental programs underway in 'dawning nations'. There is much controversy about how this money would be spent."

"As promised in Stockholm there was an Ocean Dumping Convention shortly thereafter. There was an International Whaling Commission that met. There is the International Maritime Consulting Convention which is going on right now. Mr. Train is the head of our delegation. It is a 28 day meeting to look into the cause of marine pollution from ships and what to do about it. Of course the Law of the Sea Meeting is coming up shortly. Many of the nations represented here, are involved in OECD to be sure that the pollution control activities don't cause inequities in trade."

"On a bilateral front particularly in our country, and you have all got your own bilateral activities, we have been very busy in the last two years. First, with the Canadians, we signed an agreement to clean up the Great Lakes which we hope to get really underway within five years. It's going to cost this nation something like three billion dollars if you include what the business management is going to have to pay for the plants that are polluting the U.S. shores of the Lakes. We have just completed an agreement with the Mexicans on the clean up of the Colorado River in terms of the heavy amount of minerals that we have been delivering to the Mexically Valley over the dam at the border. It was higher than in the Imperial Valley which is on the American side of the same valley, so there is naturally some unhappiness over the differential quality with the negative results for the Mexicans. We now have planned to take various steps which will make a great change in this situation. Finally, of course the low pollution power system development is one of the most important things that has happened."

"I would like to close with the thought that being here this morning reminds me of 1927. My father used to take me out to Mitchell Field on Long Island where the competition for the first crossing of the Atlantic Ocean non-stop in an airplane was coming up to a fever pitch. My father was busy in that enterprise because he worked with Commander Byrd at that time. He went to France to prepare for his trip, but he signed up Charles Lindberg to do a book on his experiences should he make the trip first. So I remember the great excitement of going out there and feeling the fever pitch of anticipation of all these men --- Lindberg, Byrd and a number of others. At the same time there were opposite numbers trying to come from the European side. There was a $25,000 prize for that enterprise and Lindberg won it. But at the same time the rest of the world gained. The very fact that so many of you came non-stop from Europe to this meeting gives one a measure of the gain that mankind got out of that enterprise. I think that what you are trying to do to find an alternative to the current polluting engine that plagues us all has some of the aspects of the excitement of a great breakthrough that is going to help not only the organization that makes that development but also all of us. And so I close my own remarks in order that you can move ahead more rapidly to that great goal."

C. Conference Remarks by Professor Nimet Ozdas, Assistant Secretary General for Scientific and Environmental Affairs, NATO

"It is a great honor and privilege for me to be present at this International Symposium on Low Pollution Power Systems Development. For me this is also a very special occasion because it is my first official visit outside of Brussels since taking up my new responaibilities, about a month ago, as NATO's Assistant Secretary General for Scientific and Environmental Affairs. Therefore, I am extremely pleased to continue in the tradition of my predecessor, Dr. Anders, who was extremely interested in all of the activities under the aegis of the Committee on the Challenges of Modern Society which we call CCMS. It is also a pleasure to observe that, like the first International Conference on LPPSD, the present symposium is convened under the aegis of CCMS."

"You may know that this committee has sponsored a number of studies using the rather innovative concept of "pilot" studies. These studies are carried out in order to cope with important urban, industrial problems confronting modern societies. Usually they are lead by a pilot country in collaboration with other countries interested in using the results of these studies in their own environment."

"One of those problems of major significance is air pollution. It is a particularly sensitive problem in view of the vital role played by air in our life support system. Furthermore, especially in our cities, we have become much more conscious of the need to improve the quality of air. In the United

States this has been reflected in such Federal legislation as the Clean Air Act of 1969 and the Amendments of 1970."

"Under the CCMS sponsorship there has been an Air Pollution Pilot Study lead by the United States in collaboration with the Federal Republic of Germany and Turkey. Furthermore, France, the Netherlands, Italy and Norway are taking active part in this endeavor. This has been one of the most successful current CCMS studies. It has achieved an impressive record and is considered as a model for other studies carried out under the aegis of CCMS."

"For example, it has devised a methodology to establish criteria for air quality assessment. Its modeling work has been of tremendous importance to the World Health Organization in devising worldwide air pollution studies. One member country, the Federal Republic of Germany, has found the results of the study extremely useful in developing legislation for air quality criteria."

"Activities of the CCMS pilot studies have won the respect of international organizations. Coming from Turkey, which has been involved in this pilot study from the beginning, I can assure you that the results thus far obtained have been of tremendous importance for the Government officials, for the public, and for the scientists in order to monitor and control the air quality of the city of Ankara. Therefore, I would like to express our thanks to the leader of this pilot study, Dr. Kay Jones, for his drive, his energy and his efficient leadership in this important study which was well received, not only by CCMS but also in my own country."

"Having elicited international cooperation so effectively, it is rather logical that the CCMS Pilot Study on Air Pollution should include as a significant element the development of a low polluting automotive engine. We know that internal combustion engines, used in automotive vehicles, based on Otto or Diesel cycles have found unchallenged application up to the '60's, 70's and may even extend beyond the 80's with new developments. This classical type of engine has accumulated the experience and developments of almost a century. It is a very reliable, versatile, flexible, and economical power unit, but also it is a source of pollution. Now a strong challenge is here for new technology as can be seen on the program of this conference. In addition to improving the performance of the classicial type of engine, the alternatives are becoming numerous and include the gas turbine, Stirling engine, the Rankine cycle engine, the battery engine, and hybrid engines. Therefore, incited by the adverse effect of pollution and driven by the never ending creative activities of the human mind, the development of a low polluting engine has become a full-fledged effort."

"In view of the industrial and commercial factors, research and development in this field has been more or less restricted to national efforts although some international cooperation has taken place. The objective is to increase the level of practical, international cooperation and to increase the eventual concrete results. The Low Pollution Power Systems Development Project reflects the value of multilateral cooperation under the CCMS aegis which is an efficient and convenient mechanism to promote the exchange and development of advanced technology. As a consequence of the Memorandum of Understanding signed last November by six member countries (Federal Republic of Germany, France, Italy, The Netherlands, and the UK and US) work on this project will be accelerated. These six nations will be joined by others, because the CCMS activities are also feasible for non-member countries, CCMS welcomes participation at the expert level to any of these activities. The broad international cooperation as reflected, by the wide representation at this conference is bound to bring us closer to the goal of clean engines for the automobile world."

"We at NATO salute your dedication and your determination to meet the challenge of our time in producing a rational engine for the industry. We are confident that the low polluting automotive vehicles of the future will be in no small part due to your efforts. I wish you every success in your endeavors."

D. Keynote Address - Robert L. Sansom, Assistant Administrator for Air and Water Programs, Environmental Protection Agency[*]

"I stand here instead of Dr. Robert Sansom, Assistant Administrator for Air and Water Programs, who was scheduled to make the keynote address. Circumstances beyond his control made it impossible for him to come. I will share briefly with you what those circumstances are. In the United States our concern with air pollution control, while focusing heavily on technology, goes beyond that and there is need for a number of cities to take action, other than to clean up individual cars, to attempt to control air pollution. In other words, it is necessary to establish some kind of controls for transportion in these cities. The Environmental Protection Agency is under court order to issue these transportation control plans very promptly. And in the United States court orders are taken very seriously. Today, Dr. Sansom has to be in Washington to announce the transportation control plans. That is why he is not here. He asked me to express his sincere regrets; he had planned to be here."

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[*] Presented by Eric O. Stork, Deputy Assistant Administrator, Office of Mobile Source Air Pollution Control, EPA

"I also take this opportunity to point out very briefly the unique nature of this meeting. This LPPSD Symposium is combined with the periodic quarterly coordination meetings that the Alternative Automotive Power Systems Program has been carrying forward for over two years now. The coordination meetings are closely related to the LPPSD effort. They began and are continued as the unique way for assuring the quickest possible communication among technical experts who are working on various aspects of the program objective, developing low pollution engines. So I think it will be most useful today and this week to combine these concerns with LPPSD and on-going activities in the United States. We now come to the remarks that Dr. Sansom would have made had he not been kept away."

"On behalf of the Office of Air and Water Programs within the EPA, I would like to add our welcome to the foreign delegations and to the other members of the technical community who are attending this symposium. We're especially honored in having Assistant Secretary General Ozdas with us today. We are especially appreciative of the kind remarks that Professor Ozdas made about the work of the EPA, particularly Dr. Jones, and other CCMS endeavors. We have found that the CCMS approach to cooperation on environmental issues has been effective in establishing communication among the technical community, both within and outside of NATO. This symposium may someday be seen as having been the cornerstone from which grew the dynamic program for cooperation in solving the many technical problems associated with our for the reduction and prevention of air pollution that comes from transportation sources — air pollution to which the passenger car contributes the largest factor."

"As you know, the United States introduced this LPPSD initiative into the CCMS forum as a part of the overall Air Pollution Conference that was held in Eindhoven in the fall of 1970. The organizational LPPSD conference was held in Eindhoven, the Netherlands the following February, hosted by our Dutch colleagues. We think it is fair to say that at that time mixed views prevailed as to the necessity of goals for alternatives to contemporary power system technology. Since that time, it is apparent that this initiative has engendered a good deal of thought regarding future air quality needs and regarding associated control technology problems. The results of this collective effort lead to the signing of the Memorandum of Understanding just about a year ago. Signatures, as already mentioned by Professor Ozdas, included Federal Republic of Germany, the United Kingdom, France, the Netherlands, Italy, and the U. S. We are also looking forward to non-NATO participation by Japan and Sweden commensurate with the open participation policy of CCMS."

"This symposium marks the first official undertaking under the provisions of the Memorandum. As you know, the other two provisions provide for the free and open exchange of information and for eventual direct collaboration on R & D projects of bilateral or multilateral interest. The first Annex to the Memorandum has been drafted and agreed to by the signing parties. It deals with protocol for exchanging technical information. The signing ceremony for this Annex will take place at the conclusion of this symposium. We of the U.S. have been developing specific methods to meet our obligations under the provisions of this Annex --- provisions which we hope will set the tone for dynamic and meaningful information exchange."

"In the United States we initiated the Governmental efforts to develop alternative engines for automotive use almost four years ago. We did this because of the need to ensure that the low emission requirements of future automobiles would be met. To this effort, we have in the past year added yet a new parameter that weighs heavily in our current decision making. Even as little as four years ago, we did not give a great deal of thought to the issue of fuel economy of cars. Fuel supplies, except to perhaps some experts or to some who seemed to be alarmists, seemed inexhaustable for the foreseeable future. How quickly such views can change. But they have of course changed."

"Whereas we originally paid little attention to the fuel economy characteristics of the alternative engines that were being developed or the fuel economy characteristics of existing cars for that matter, fuel economy characteristics have now become a major factor in our selection from among competing approaches for development. There is currently active consideration within the U. S. Government of a major effort to attempt to develop engine systems that will be much more fuel efficient than our current engines."

"There is also consideration of other things that can be done to improve fuel economy. Smaller cars, radial tires, fewer power consuming accessories are among the obvious alternatives. It appears to us that the LPPSD effort as it develops further might usefully be broadened to encompass the current and continuing problem of expanding demand for fuel and the increasing difficulty of providing such fuel supplies. Fuel shortages are not limited to the United States. They effect all developed countries. Thus it may prove useful to tap the international talent that is represented at this conference and that is represented in the total LPPSD program, not only to achieve low emission vehicles, but also to achieve concurrently vehicles that can get along on substantially less fuel than do today's vehicles."

"One other factor, that might be given further consideration would be the establishment of close coordination between the activities aimed at low polluting and, we hope, fuel conserving vehicles and the activities of the CCMS Experimental Safety Vehicle Project. The ESV Project, because of its nature, has in the past tended to increase the weight of vehicles that were designed to meet safety goals --- increase these weights well over the weights that were targeted for such vehicles. As we all know, vehicle weight is the single most important factor that effects fuel economy of vehicles today."

"You have important work to do here this week. You will be reviewing the status of technical development and will be charting a course for future action. I know that you agenda is full, indeed very full; we are already 10 minutes beyond time of the agenda. Let me thus use no more time from your busy schedule. Let me conclude by welcoming you once more and by expressing my appreciation to you for having come very great distances to this important meeting."

E. Overview of Low Pollution Power Systems Programs in Participating Countries

1. United States - J. J. Brogan, Director, Alternative Automotive Power Systems Division, EPA

There are two major program activities in AAPS Division -- engine hardware and new mission activities. The engine hardware programs are to objectively determine if the individual alternative systems are viable, practical replacements to the conventional spark ignition engine. Work was started in 1970, because of uncertainty as to the ultimate capability of the conventional engine to satisfy emission requirements and still be a practical, versatile engine. (This uncertainty still continues.) Hence, programs were initiated on Rankine and Brayton cycle engines. The intent is to evaluate these engines by test in practical demonstration vehicles by 1975.

Because almost no serious recent effort to apply advanced technology to automotive Rankine engines was apparent, these engines were started from preliminary designs. The Brayton cycle program, on the other hand, takes advantage of recent work and investment of the automotive industry on this type of engine. Prime effort is focused on solution of the chronic problem areas already identified as barriers to the early production of gas turbines. The results of this work are being integrated into a carefully selected baseline engine for the 1975 demonstration tests.

It is emphasized that the basic job is to evaluate.

The new mission work, recently started, encompasses studies on:

- Alternative fuels for surface transportation from domestic, non-petroleum sources. These include liquid or gaseous fuels from coal, tar sands, shale, etc. and fuels such as methanol, ethanol, and hydrogen.
- The potential role of electric vehicles. The Los Angeles area is being looked at specifically to ascertain the impact on air

quality, electric power consumption, and natural resources such as copper and zinc.

- An annual summary is being prepared covering world-wide activities on alternative engines and fuels. Initial publication is expected in the late spring of 1974.

2. United Kingdom - George Donald, Superintending Engineer, Vehicle Engineering Division, Department of Environment, London, England

England is more moderate than the U.S. in its emission requirements, due largely to different climatic conditions, and is looking more toward control systems which do not add appreciably to vehicle cost or its fuel consumption. Activities encompass:

- lean mix systems
- heat pipes
- catalytic systems which are lead tolerant
- systems to remove lead from the exhaust
- electric vehicles including some advanced battery systems.

The need for emission control is certainly recognized, but it is believed that the requirements in England and Europe are more limited than in the U.S..

3. Sweden - Olle Ljungstrom, Section Head, Transport Systems, R & D Planning, Swedish Board on Technical Development

Three departments in the Technical Development Agency of the Swedish Government are concerned with transportation systems, vehicles, powerplants, and emissions: Energetics Department, Transportation Department, and Environmental Protection Technology Department. Each of these departments operate on an annual budget of about $2.5 to $3 million. About $0.8 million is spent on the two main engine programs: Stirling engine and gas turbine engine.

Other nominal investigations by various agencies are concerned with electric vehicles, batteries and fuel cells. A number of government laboratories are involved in emission and noise tests on Otto and Diesel engines. Sweden is also participating in the U.S. Experimental Safety Vehicle (ESV) Program.

The Swedish automotive industry produces a large number of cars, trucks, and buses which are backed up by extensive R & D effort. Work by Saab Scania on Rankine systems is reported in Section IV-B. Work by SRM on rotary engines is summarized in Section VII-B.

4. The Netherlands - J. G. Kuiperbak, Highway Traffic Service

Vehicle concentration in The Netherlands is about 1 car per 4 people; however, the population density is high, particularly in the West where it is about 2500 people per square mile and also where there is a large concentration of petrochemical industry. Thus, although climatic conditions do not generate significant photochemical smog except for a few weeks in the Fall, there is a growing concern about road transport air pollution. The government would like to see more stringent air pollution controls. Research in this area is being encouraged.

Of equal concern is the noise and smoke emissions from Diesel engines.

Work on both conventional and unconventional engines is embodied in three principle programs:

- Application and demonstration of Stirling engines to city buses by Philips, N.V. and DAF. A feasibility study of broader application was included. These engines have very low emission and noise characteristics.
- A shorter term program by DAF is in progress to improve the noise and emission characteristics of Diesel engines. Improvements are to be available in 3 - 4 years.
- Emissions from small 2-cycle engine motor bikes (high density in Holland) varies from 30% to 100% of those from passenger cars. Work is in progress to clean up these conventional engines.

5. Italy - V. Opportuno, Ministry of Transportation (Presented by G. Savonuzzi, Fiat)

Initial efforts were to assess atmospheric problems by making measurements in the main cities. Also the automotive industry was encouraged to seek improvements in the present engines. Much work was done. Since many Italian cars are exported to the U.S., their standards must be satisfied. So far Italian vehicles have passed the requirements with internal improvements. In planning for the future, work is also being done on external emission control devices. The Diesel engine is also getting attention.

Alternative engines such as gas turbines and steam engines are being evaluated. The gas turbines show promise in some areas; the steam engine tests did not show as much promise. Problems with electric systems include batteries, motors, and complex expensive electronic controls. Some consideration is being given to hybrid systems for low emission buses.

6. Federal Republic of Germany - Dr. D. Hartmann, Ministry of the Interior

The approach in Germany is to achieve emission levels equal to 1/10 of 1969 levels by 1980 (1980 levels are equal to stringent U.S. 1976 levels), by improving the conventional spark and Diesel engines.

Further reduction in emissions are expected from alternate engines. Some of the work to date includes:

- Gas turbines and stratified charge engines at VW
- Electric systems at Daimler Benz
- Stirling engines at M.A.N.

By the year 2000 it is anticipated that alternative non-fossil fuels will be required.

The German government is supporting short range work on improvements in spark ignition and compression ignition engines including stratified charge, fuel preparation, after-burners, and electronic controls. Long range development work is being supported on gas turbines, Stirling engines, and Rankine engines.

Improvements in the organization and coordination of R & D work on low pollution power systems are being implemented over the next 12 months.

7. France - C. Lamure, Transport Research Institute

It appears the present pollution conditions in France do not seem to be annoying, but serious problems may arise from the increasing number of vehicle owners, and from urban and demographic development.

The immediate objective is to keep the present actual level of pollution in dense urban areas in France from increasing.

Acknowledging the faster increase which is expected in the peripheral zones of densely built-up areas, recommendations were made to reduce the carbon monoxide and hydrocarbon emissions below the standards defined in Regulation No. 15 of the Economic Commission for Europe, of the United Nations.

The discussions that followed in the European working groups indicate that E.E.C. should modify the present rules of the "Regulation No. 15" by 15%, starting October 1st, 1975.

The present discussions about nitrogen oxides take the three following factors into account:

- The little knowledge about noxious effects of NO_x;
- The small probability of smog appearance in Europe with the present state of traffic;
- The necessity of not increasing the present pollution levels in dense urban areas.

Research on non-polluting engines is largely devoted to improving conventional engines for which the chosen standards seem to be achievable.

Among the European objectives, reduction of noise levels is more important to the French people than air pollution. The long term objectives entail important decreases of noise levels, particularly for lorry engines.

Unfortunately only a small amount of information is available on noise emissions from non-conventional engines such as the Rankine, gas turbine, or Stirling engines.

F. Summary of Significant Comments Concerning Activities of the NATO/CCMS Initiative

The following are important comments and suggestions which resulted from the introductory remarks, the above individual panel presentations, and the ensuing discussions from the floor.

- There appears to be a need for the NATO/CCMS program to broaden its perspective beyond the technical and related economic aspects of engine system development to include problems related to energy conservation, noise suppression, and vehicle safety. It was suggested that NATO/CCMS might desire to address itself to studies looking toward the need for an approach integrating all of these aspects and relating these to the entire spectrum of society requirements.

- The need for technology assessment within the NATO/CCMS LPPSD program was suggested as a means to better focus on the problems associated with future cooperative activities and thus allow a more meaningful comparison of alternative approaches by different countries. Specifically, it was suggested that the NATO/CCMS group give consideration to joint determination of a set of criteria for this purpose. Such criteria might include all pertinent factors such as weight of vehicle, fuel consumption, maintenance, reliability, cost, users assessment, etc..

In a special evening session on technology assessment criteria a startling divergence of viewpoints on the subject was readily apparent. This accents the need for more international effort to clarify the objectives, means for implementation, and the real value of technology assessment investigations. Of particular interest is the necessity of putting complete technical information about alternatives and possible consequences in the hands of the public in understandable terms.

- The possibility of effects of automotive emissions, combined with other sources of pollution, on global climate resulting in irreversible ecological effects was posed as a serious question needing resolution in order to evaluate the total international effort, as well as each country's individual effort, to control motor vehicle pollution.

- An evaluation of the total international effort in research and development on low pollution power systems, compared to the projected annual economic penalties estimated as needed to meet motor vehicle emission standards, was posed as a necessary input item to determine the magnitude of the economic gains to be expected from these research development activities. Such information on an international basis would be helpful to assess the viability of the NATO/CCMS initiative and the possible need for further development of the program.

Points Clarified during Question/Answer Period:

- A new generation of solid fuel (wood or coal chips) gas generators is being developed for modest production (500,000 units). Such gas generators were used in World War II. About 70% of rated power can be achieved on CO; with 10% gasoline mixture, 80% power can be achieved. Several miles per gallon of chips can be obtained.

- The Siemens' carburetor uses a catalytic device in front of the engine instead of in the exhaust. It is not expected to be available until about 1980.
- The U.K. believes noise is of equal or greater importance than gaseous pollution. Control legislation is in progress.
- Noise emissions have not been emphasized in the U.S. AAPS program (although targets are established) because no legal standards have been established. However, EPA has just recently received legislative authority to move ahead in establishing noise standards on a number of types of machinery, including automobiles.
- Noise reduction programs are being actively pursued in Sweden. Tires are getting more emphasis than engine noise for automobiles.
- The Honda stratified charge engine is considered an alternative engine. It looks very promising, but more needs to be known about it. Some American companies, as well as EPA, are actively evaluating the Honda CVCC engine. EPA does not plan to duplicate development effort that is going on elsewhere. Because little or no work was in progress on Rankine or gas turbine systems for automobiles, EPA initiated work in this area so that reliable data would be available for important decisions on future development direction.

II. STIRLING ENGINES

A. "State of the Art of the Development of the Stirling Engine with Emphasis on the Low Pollution Potential and Low Fuel Consumption" by A. P. J. Michels and R. J. Meyer of Philips Research Laboratories, N. V. Philips, Eindhoven, Netherlands

The Stirling engine is based on a closed cycle. If such an engine is pressurized with a gas and is heated at one place and cooled at another, an outcoming shaft will rotate and will give mechanical power. Research into the Stirling engine formerly known as the hot-air engine, was begun at Philips in 1938. At that time the company was looking for a heat-driven electric generator for radio receivers and similar equipment so that they could be used in parts of the world without a public electricity supply and where the fuel needed for such a generator would be easier to obtain than batteries. The hot-air engine was eventually chosen because it met the requirements for the proposed application; ie. quiet operation, suitable for a variety of fuels (a "multi-fuel" engine) due to the external heating system, and a long life because of the closed gas system.

A variety of prototype engines were built, developed and demonstrated in a number of applications. Power levels ranged from very small fractional horsepower ratings to 10, 40, 100, 200 and 400 HP ratings; applications included: yacht, generator sets, a riding mower. The most ambitious of the recent programs has been the installation of a 200 hp in-line design (Fig. 1) in a DAF bus which has been demonstrated in the Netherlands for the past two years (Fig. 2).

Up to this point the weight and size of the engines built and installed had been more comparable to the Diesel engine than to the light weight gasoline engine. When it became apparent in the mid-1960's that the solution to the emissions problem in the United States with the present automotive engine may be insurmountable, Philips redirected its research to programs in the light weight and compact engine area. These configurations had been investigated earlier, but were shelved due to several problems which at that time

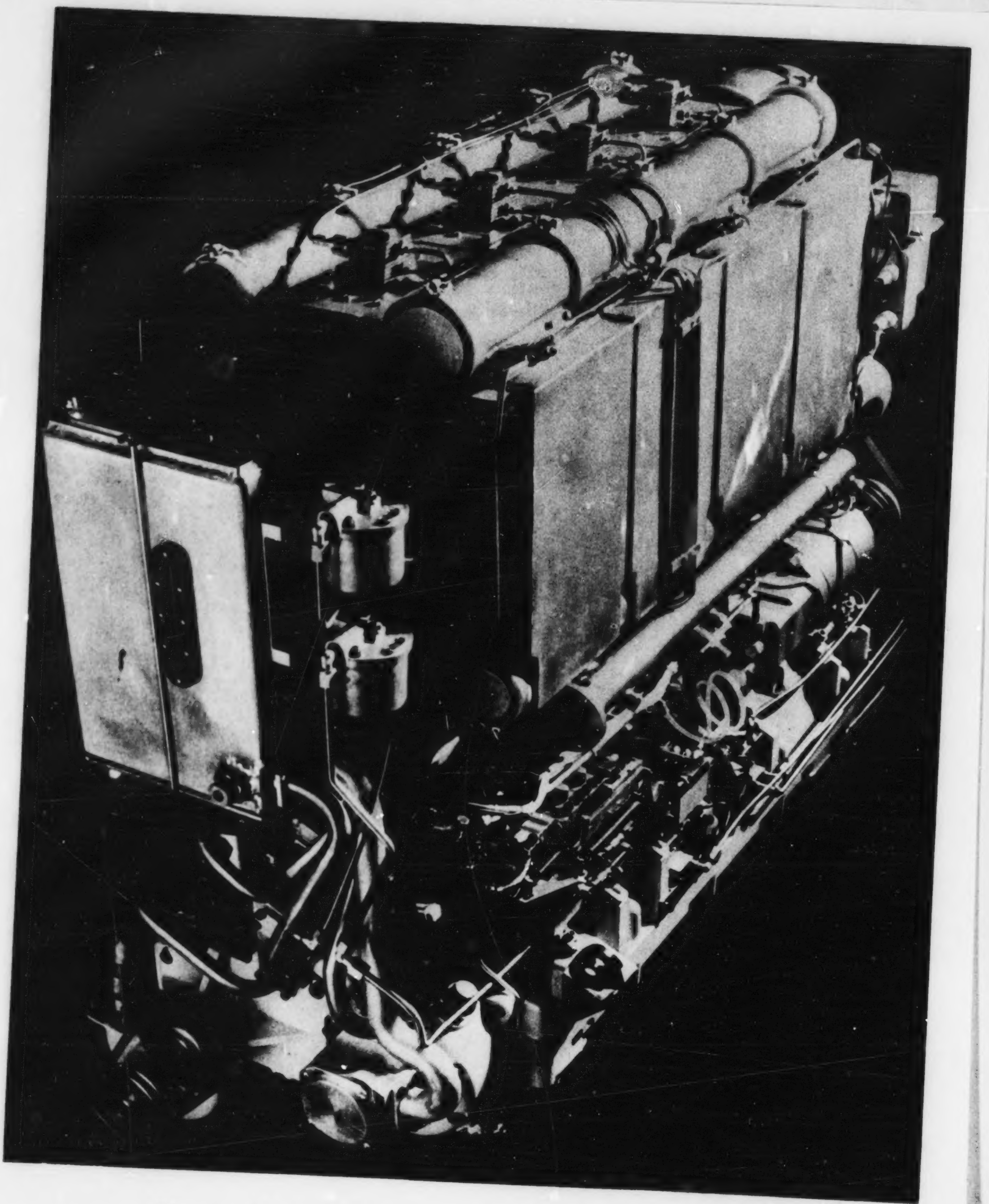


Fig. 1 200-HP, In-Line Stirling Engine Used in DAF Bus

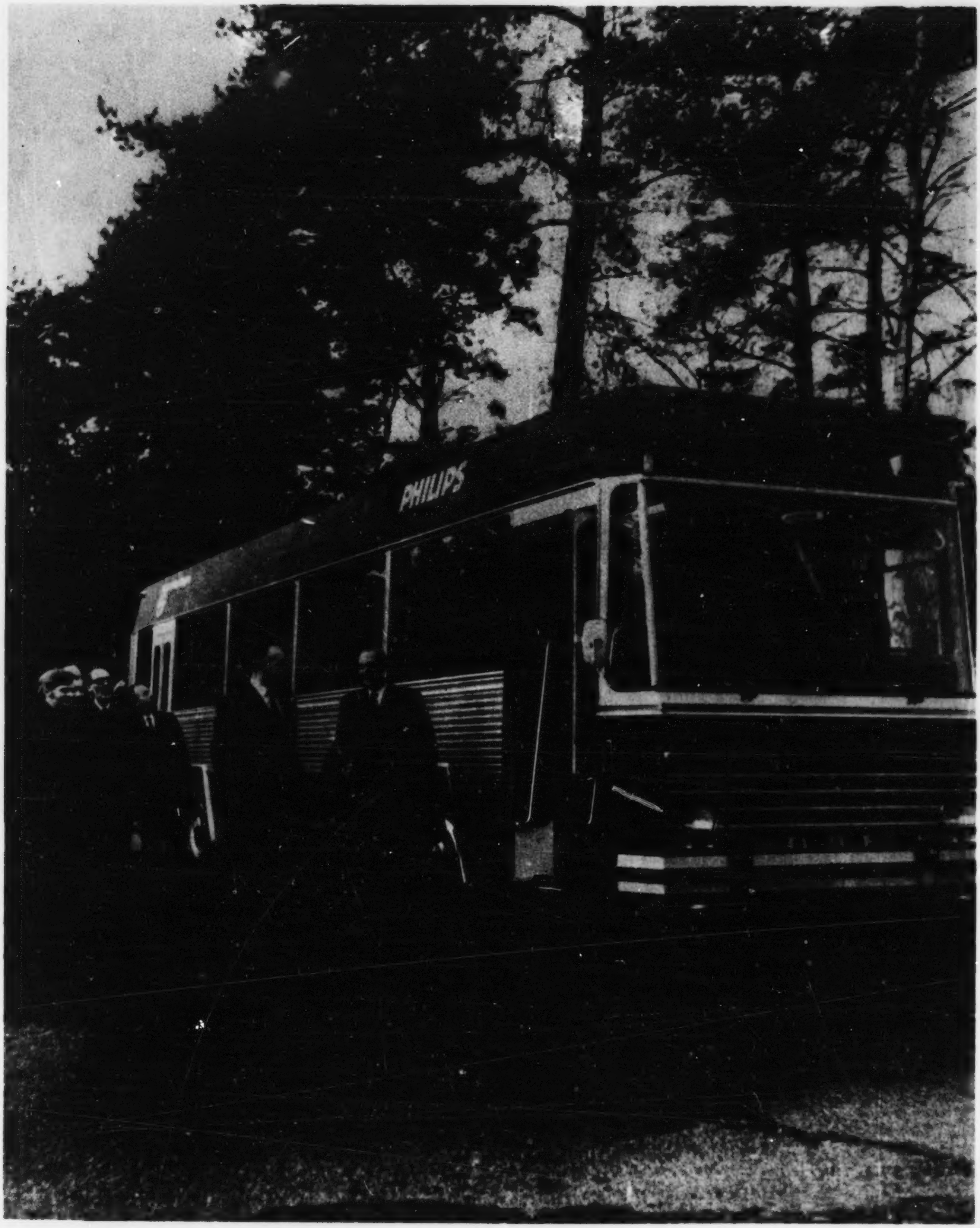


Fig. 2 DAF Bus Powered by 200-HP Stirling Engine

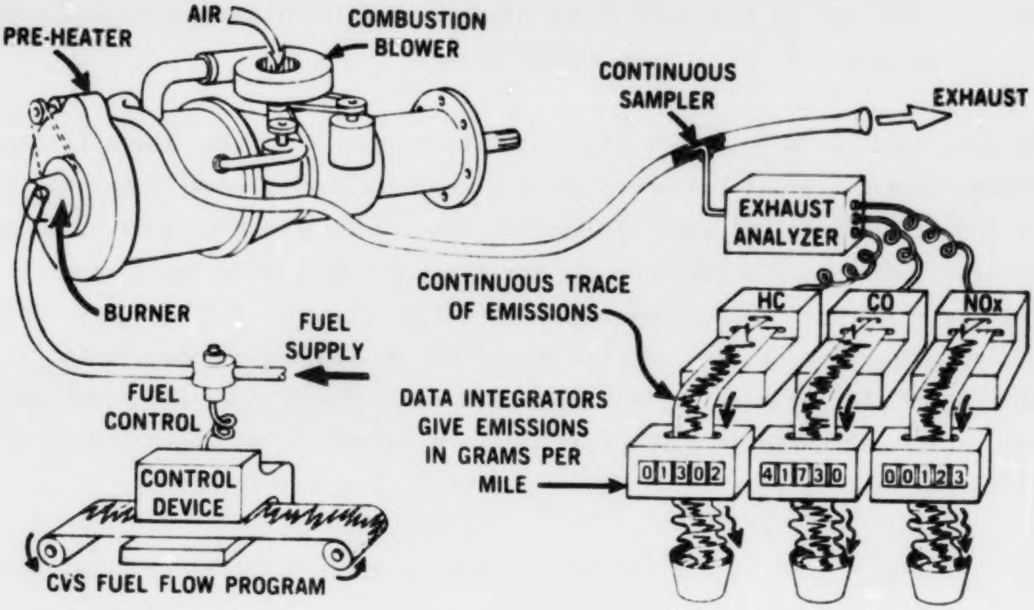
could not be solved with available technology. A second generation concept evolved from all of this work which offers a simple, light weight and compact engine suitable for automotive applications.

At this point it should be noted that Philips had considered the Stirling engine as a potential product only in fractional horsepowers to expand sales of electrical and electronic equipment. The engines with outputs of 10 to several hundreds of horsepower did not fit into the production scheme of Philips and therefore Philips decided to find licensees for this type of engine. As early as 1958 General Motors became the first licensee but terminated the contract in 1970. In 1968 two German companies -- MAN and MWN, and in the same year the consortium United Stirling Sweden became licensees of Philips.

Philips also contacted U.S. industry and government agencies starting in late 1970 to explore the possibility of Stirling engine development for vehicular applications in the U.S.. Contacts were made with several engine manufacturers as well as the Environmental Protection Agency (EPA), Department of Transportation (DOT), the National Academy of Sciences (NAS), Office of Science and Technology (OST), and Advanced Automotive Power Systems Office (AAPS). Although the EPA expressed an interest in the development of Stirling engines no support could be given due to existing constraints on funding. The Department of Transportation was also interested in the Stirling engine for the bus application as well as several other areas in the field of ground transportation. However, Ford did initiate an internal program in cooperation with Philips to investigate the potential of the second generation Stirling engine as an alternative power plant for the internal combustion piston engine. As a result of this study, the Ford Motor Company became a licensee of the Stirling engine in mid-1972.

One of the most important requirements of this study was the demonstration of the emissions potential of a full scale Stirling engine combustor. Philips designed and built a full scale test rig and tested it to the CVS test cycle specified in the Federal Regulations. The results of the initial test are shown in Fig. 3. The results are valid for a car with a

CVS TEST SIMULATION


PRE-HEATER
AIR
COMBUSTION BLOWER
CONTINUOUS SAMPLER
EXHAUST
EXHAUST ANALYZER
CONTINUOUS TRACE OF EMISSIONS
HC
CO
NOx
BURNER
FUEL SUPPLY
FUEL CONTROL
DATA INTEGRATORS GIVE EMISSIONS IN GRAMS PER MILE
01302
41730
00123
CONTROL DEVICE
CVS FUEL FLOW PROGRAM

RESULTS OF CVS TEST SIMULATION

(GRAMS PER MILE)

CONSTITUENT	STIRLING BURNER	1976 STANDARD
UNBURNED HYDROCARBONS	0.20	0.41
CARBON MONOXIDE	1.20	3.40
OXIDES OF NITROGEN	0.14	0.40

Fig. 3 CVS Test Simulation and Test Results

curb weight of 4600 lbs. equipped with a 170 BHP Stirling engine. The latest results also indicate that unburned hydrocarbons are one half the level specified by the Federal Standards. Carbon monoxide is less than one third of the standards, and oxides of Nitrogen are less than one half those specified.

Therefore, with a 200 hp engine (substantially larger than the expected average engine of the future) the population of automobiles so equipped could double under the worst condition, which is for NO_x, and still have the same pollution effect as if all cars were able to meet the 1976 Federal Standard.

The economy projection of the Stirling engine also is very attractive for the automotive application. Figure 4 illustrates the miles per gallon projections for the Stirling engine versus a 1976 internal combustion engine with emission controls. The Stirling engine averages across the board 50% better than a 1976 IC engine with emission controls on lower grade fuels. It is also significant to note that the maintenance of emission levels for external combustion continuous burning type engines should be quite good. Such a system is similar to the familiar home oil burning furnace which exhibits very high reliability and long life.

Another of the Stirling engine's striking properties is quietness. The quiet operation is due to: the absence of sharp pressure fluctuations (no explosions take place), the absence of mechanical valve noise, and full dynamic balancing of the drive system.

An artist's view of the 200 hp Ford-Philips automotive engine is shown in Fig. 5. Figure 6 shows the parts of the engine to illustrate its simplicity and adaptability in a majority of parts to conventional manufacturing techniques. Figure 7 shows a mock-up of the same engine before installation in a vehicle. A comparison of the V-8 engine removed from the Torino car and the Stirling engine shows that the two engines are approximately the same size for the same output. The mock-up engine installed in the automobile with all structural components in place required no changes

ECONOMY PROJECTION

MILES PER GALLON

CRITERIA	STIRLING		INT. COMB. 351-2VC	INT. COMB. 351-2VC DERATED 15% FOR EMISSIONS
	DIESEL	GASOLINE		
30 MPH STEADY SPEED	29.0	23.8	19.3	16.4
40 MPH STEADY SPEED	28.9	23.7	20.2	17.2
50 MPH STEADY SPEED	26.6	21.8	19.1	16.2
60 MPH STEADY SPEED	23.4	19.2	17.1	14.5
70 MPH STEADY SPEED	20.3	16.6	15.3	13.0
30-70 MPH AVERAGE	25.6	21.0	18.2	15.4
CITY	13.9	11.4	9.6	8.2
SUBURBAN	21.8	17.9	15.7	13.3
CUSTOMER AVERAGE	17.9	14.7	12.7	10.7

VEHICLE ASSUMPTIONS AND WEIGHT COMPARISON

	STIRLING ENGINE CAR	BASELINE CAR
ENGINE	170 HP DOUBLE ACTING SWASHPLATE ENGINE	351-2V V-8 INTERNAL COMBUSTION ENGINE
TRANSMISSION	C-4 AUTOMATIC	C-4 AUTOMATIC
ACCESSORIES	P/S, P/B, A/C, RADIO	P/S, P/B, A/C, RADIO
CURB WEIGHT	4241 LB.	4283 LB.
PERFORMANCE WEIGHT	4541 LB.	4583 LB.

Fig. 4 Economy Projection and Weight Comparison

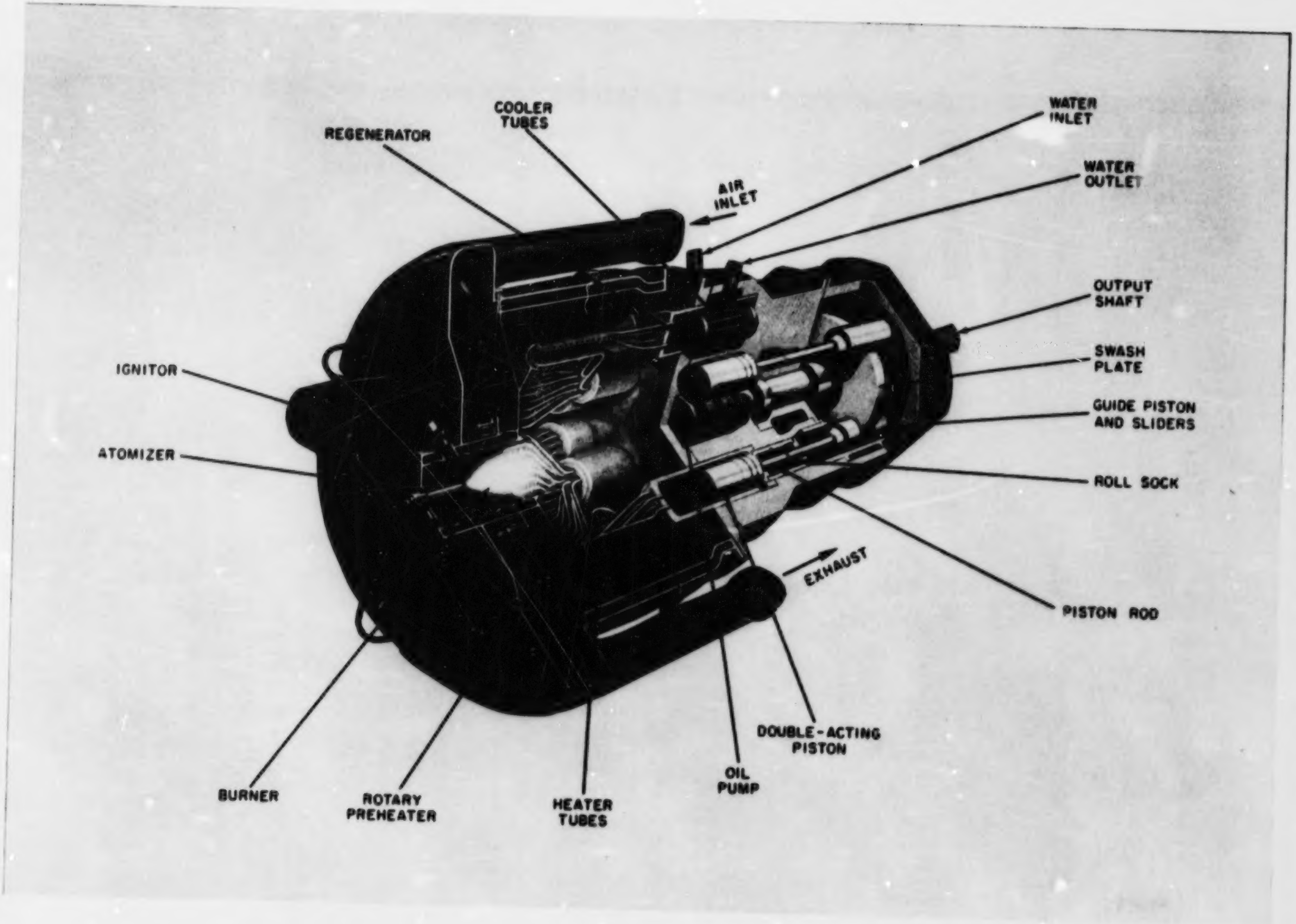

REGENERATOR
COOLER TUBES
AIR INLET
WATER INLET
WATER OUTLET
OUTPUT SHAFT
SWASH PLATE
GUIDE PISTON AND SLIDERS
ROLL SOCK
PISTON ROD
EXHAUST
IGNITOR
ATOMIZER
BURNER
ROTARY PREHEATER
HEATER TUBES
OIL PUMP
DOUBLE-ACTING PISTON

Fig. 5 Drawing of 200-HP Ford-Philips Automotive Engine

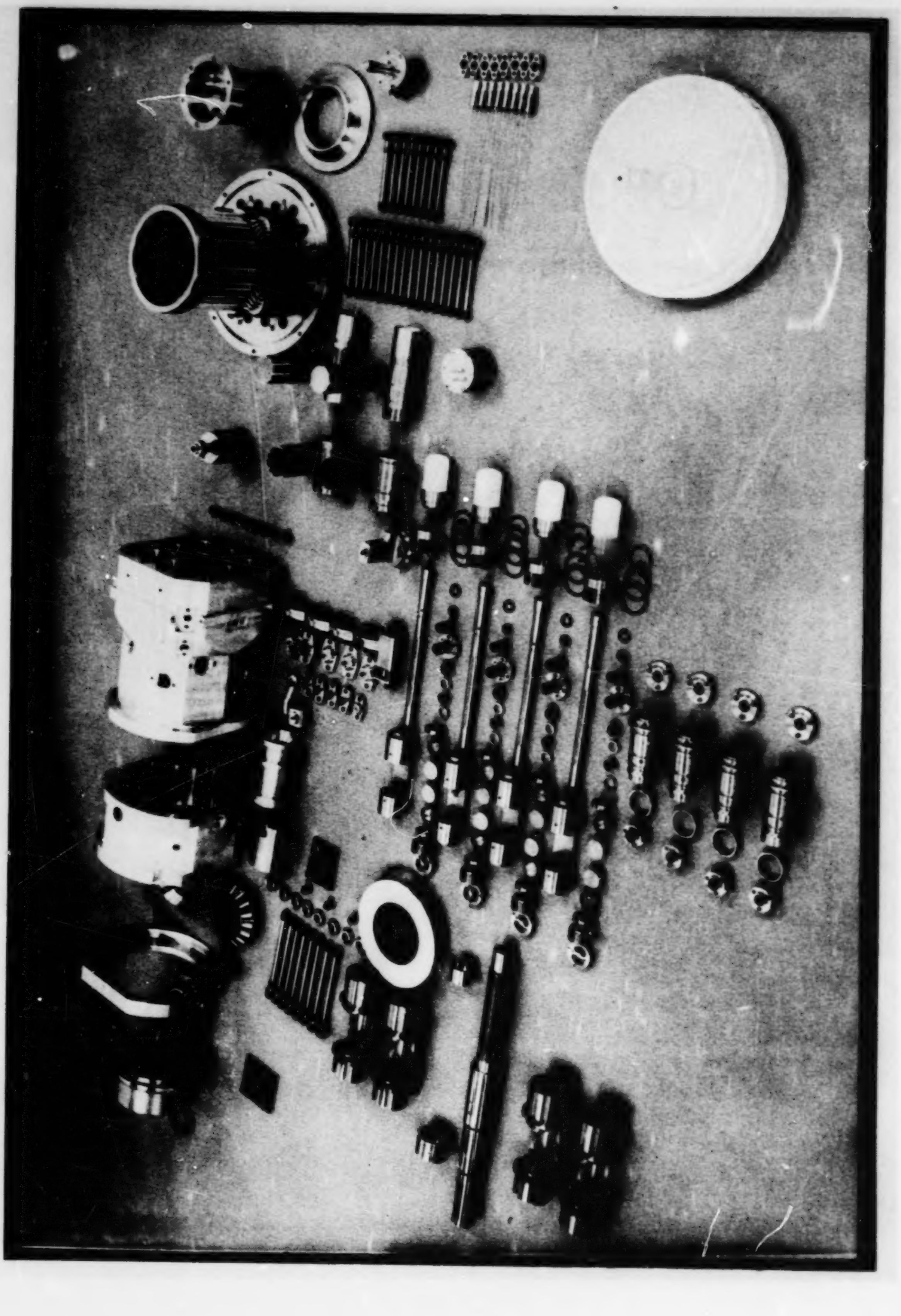


Fig. 6 Disassembled Ford-Philips Sterling Engine

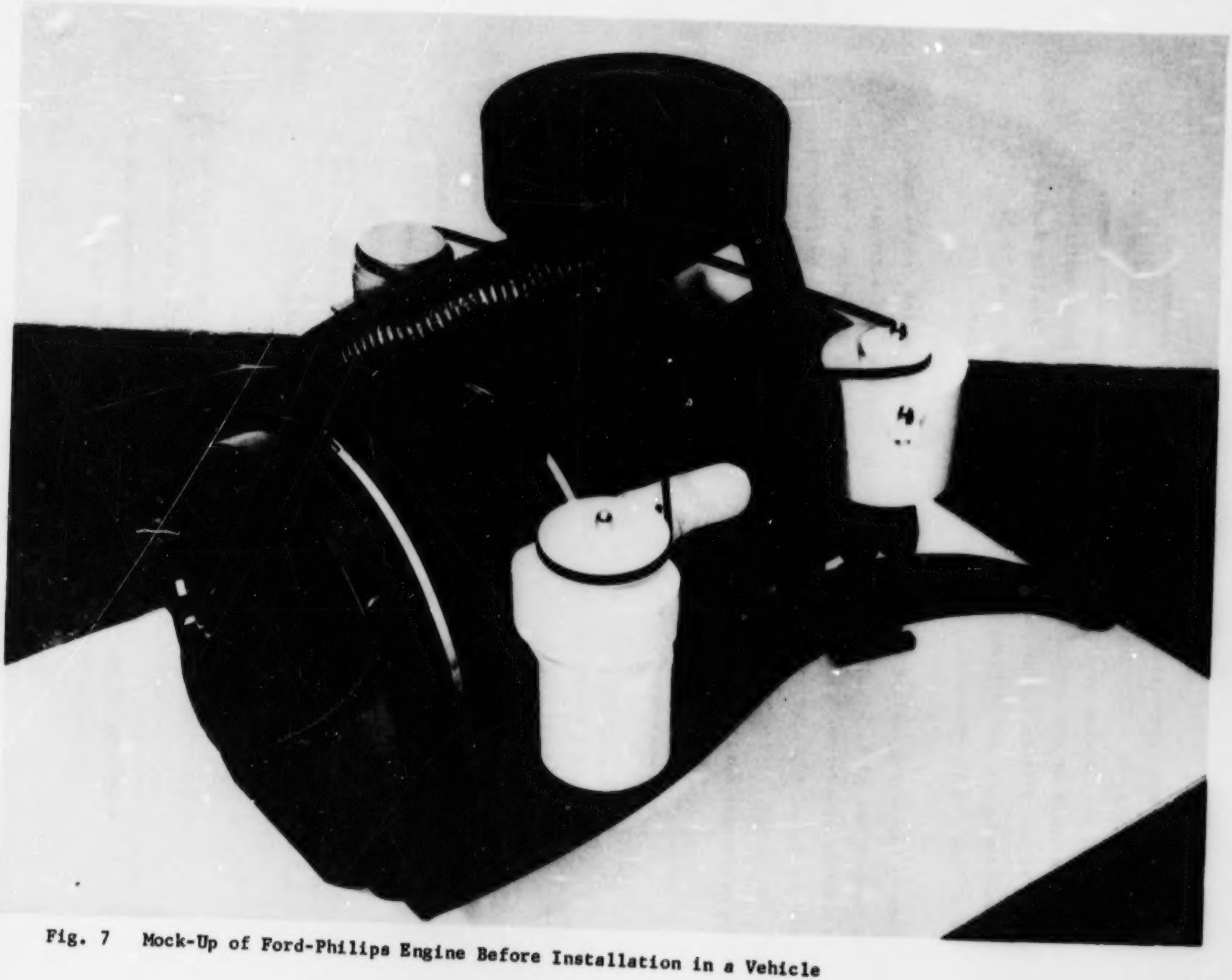


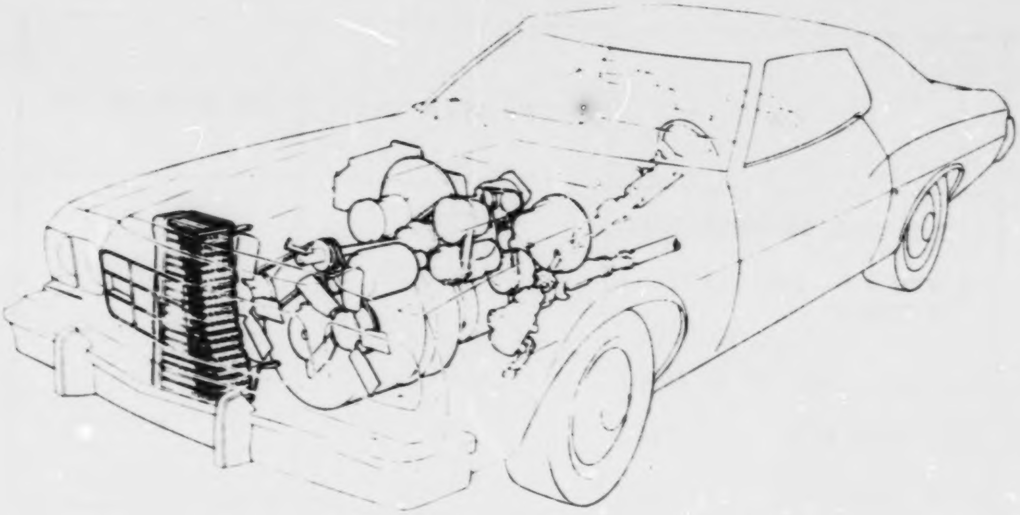
Fig. 7 Mock-Up of Ford-Philips Engine Before Installation in a Vehicle

in vehicle length, suspension, steering or structure to accommodate the engine (see Fig. 8). This important similarity in configuration permits adoption of this engine as an option for the car model and also permits the replacement of the engine in older vehicles without major modification. Figure 9 lists the performance projections of the Stirling Engine. It indicates that the performance of the Stirling car is equal to or better than the pre-emission controlled gasoline engine car.

There is the strong belief within Philips that, if the engine can be made as compact and light weight as they believe is possible, the extremely attractive properties of the engine, especially for the environment, should make it one of the most important advances in engines that can be foreseen in the future. Briefly the desirable properties of the Stirling engine for the automotive application are:

- Very Low Emissions - Can be far better than the requirements set forth in the 1976 Federal Standards.
- Fuel Consumption - Better than high compression ratio gasoline engines before emission controls.
- Very low noise level engine with practically no vibration. (Measured according to SAE J366: for DAF bus - max of 68dBA)
- Capability to operate on a wide range of fuels without engine modifications. This range of fuels includes the conventional automotive grades as well as virtually all other kinds of liquid fuels as well as gaseous fuels such as propane or butane.
- Long Service Life- which is inherent to the closed cycle system.
- No Lube Oil Consumption or oil changes required.
- Reliable Starting under all conditions.
- Performance Characteristics of the engine are equal to or better than the internal combustion engine before emission controls.
- Economy of Operation should be better than the internal combustion engine before emission control because of the ability of

1973 TORINO WITH PHILIPS STIRLING ENGINE



STIRLING ENGINE
PACKAGE

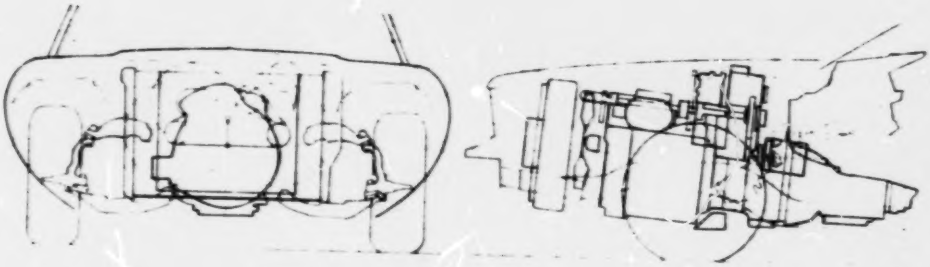


Fig. 8 Stirling Engine Installation in 1973 Ford Torino

CRITERIA	STIRLING # 4-215	INT. COMB. 351-2VC
0-10 SECOND DISTANCE (FEET)	491	484
50 MPH TIME EXPOSED (SEC.) TO DANGER	9.2	9.3
0-60 MPH TIME (SEC.)	11.1	11.1
25-60 MPH TIME (SEC.)	8.0	8.0
50-80 MPH TIME (SEC.)	11.2	11.3

Fig. 9 Performance Projection of Stirling Engine

the engine to use low grade fuels and the high efficiency of the engine under all operating conditions.

- Engine can be designed to fit as a replacement or new engine into existing or future automobiles. Engine design is proven by over 100,000 hours of test experience without a single failure that was not self-contained or repairable.
- Experimental engines have all been built using conventional tooling and manufacturing techniques.

Digressing briefly, the Stirling engine is exceptionally versatile in that it offers the possibility of solutions to the emissions problem by using energy sources other than conventional fuels. One engine has operated on 10 different liquid fuels as well as some gaseous fuels. A "zero pollution" engine running on stored heat has been built and tested (See Fig. 10). This concept allows thermal recharging after a period of operation similar to the electrical recharge of a battery-powered vehicle. Using this concept, an automobile using a "zero pollution" engine would have a propulsion system weight and volume of approximately one-eighth of that of a comparable rated lead-acid storage battery power system.

It is also very easy to use hydrogen - which many believe will be the fuel of the future - to run the engine. Philips has developed a safe storage technique which provides for storage of hydrogen at room temperature, at low pressure, at almost twice the density of liquid hydrogen with virtually no possibility of explosion even when the container is ruptured by damage (Fig. 11). To demonstrate how universal the heat source for the Stirling engine can be, a coal fire has been used to generate heat which runs a small Stirling engine which in turn powers a generator set, lighting four fluorescent lamps.

All of the above represents the results of more than 30 years basic research and advanced development work. It is believed that Philips has now done its part on its own resources in pioneering the development of the Stirling

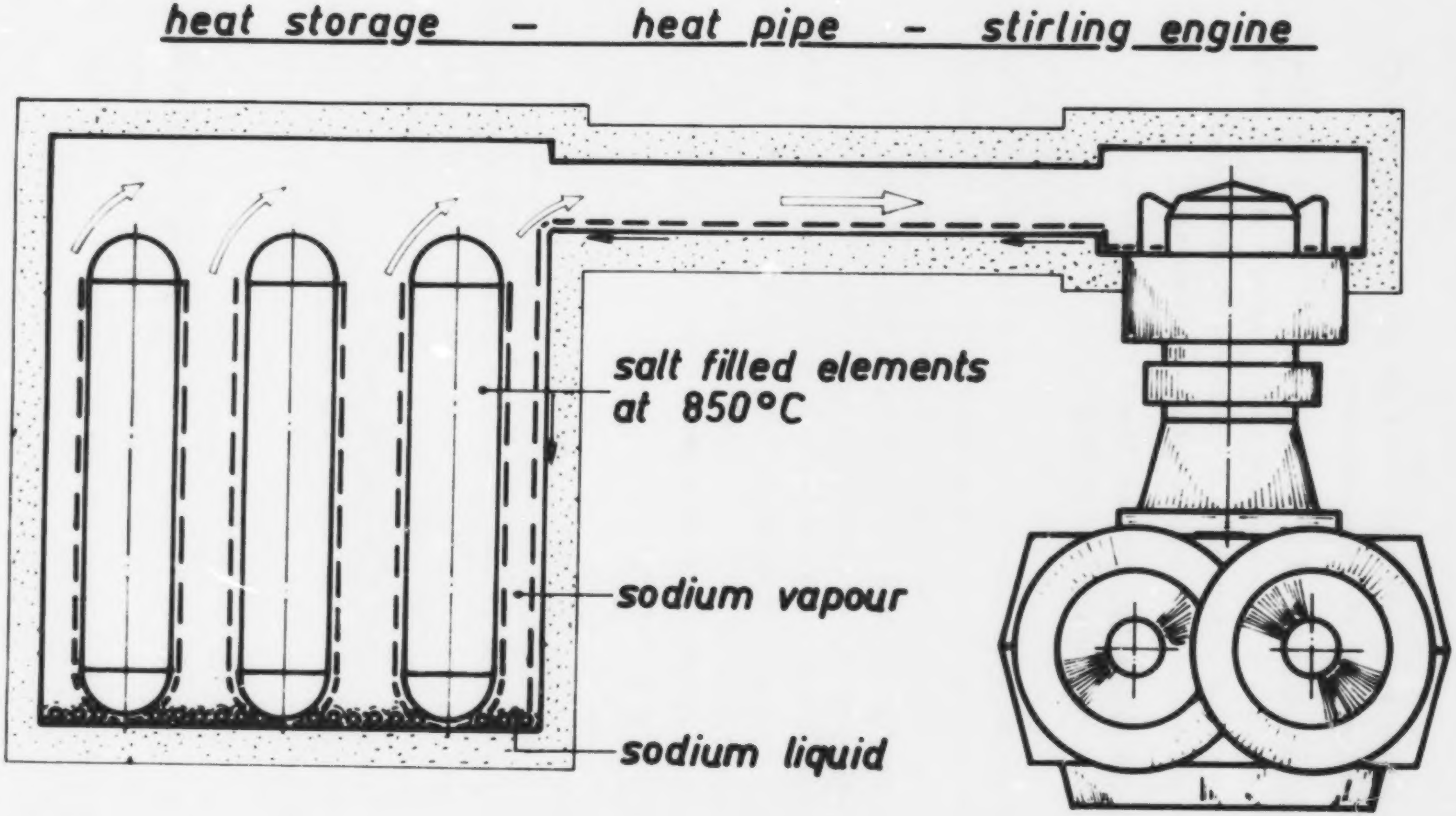
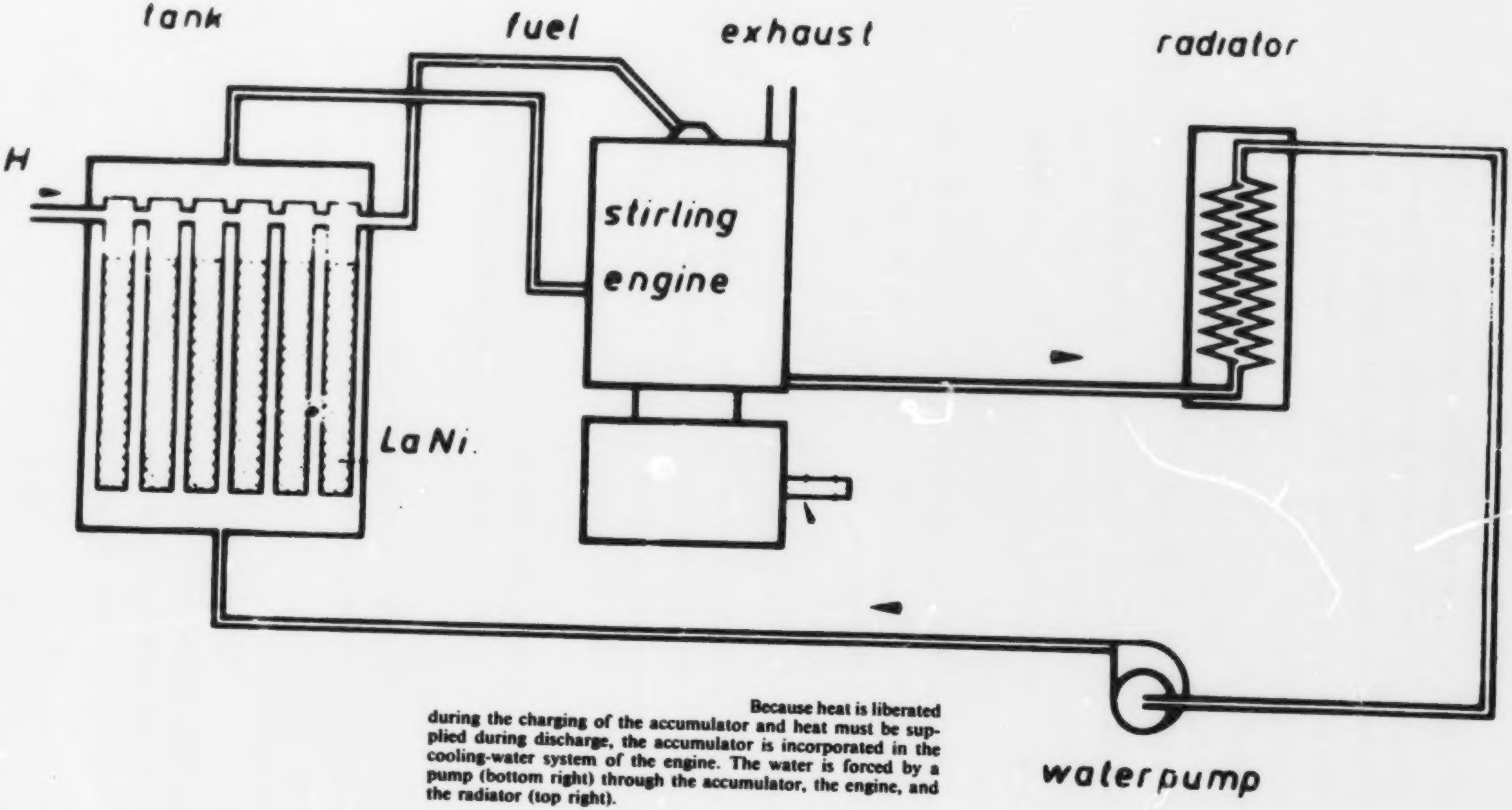

heat storage - heat pipe - stirling engine
salt filled elements at 850°C
sodium vapour
sodium liquid

Fig. 10 Zero Pollution Engine


tank
fuel
exhaust
radiator
H
stirling engine
LaNi
waterpump

Because heat is liberated during the charging of the accumulator and heat must be supplied during discharge, the accumulator is incorporated in the cooling-water system of the engine. The water is forced by a pump (bottom right) through the accumulator, the engine, and the radiator (top right).

Fig. 11 Schematic Representation of a Stirling Engine (Center) With $LaNi_5$ Hydrogen Accumulator (Left).

engine. It is now at the stage in research and development that optimizations and designs for specific applications must be done. Starting with the vehicle application, many things have been identified which can be done to simplify the engine especially in the field of smaller outputs for more compact vehicles. There is still a lot of work to be done to make the engine ready for volume production.

Points Clarified during Question/Answer Period

- Exhaust gas recirculation was defined on the basis of the fresh air taken into the engine. A 100 percent EGR is reached when the exhaust gas taken in (or recirculated) is equal to the fresh air taken in.
- The Stirling engine being built for Ford will be about 50 lbs heavier than the original gasoline engine without emission controls. This comparison does not include the cooling system for either engine; however, the weight of the two cooling systems should not differ appreciably.
- Theoretically, the compression and expansion is isothermal. The transfer of fluid from compression to expansion chambers is done at constant volume. The theoretical Stirling engine efficiency should equal the Carnot efficiency.

B. "Development of Stirling Engines in Sweden: Review of Recent Progress and Current Activities" by L. G. Ortegren, KB United Stirling (Sweden) AB & Co., Malmo, Sweden

Background: United Stirling is a development consortium of Swedish organizations comprising a major shipbuilding company, a manufacturer of small I.C. engines, and the Swedish Government. It has been pursuing Stirling engine development about four years.

After building and testing several prototype engines of the displacer type (ranged from 2 KW to 150 KW) in boats, generator sets and an MAN bus, development for automotive applications was focused on the other basic type of Stirling engine -- the double acting type. Key reasons for this change were superior size, weight, and cost of the double acting types. Emphasis is on medium duty automotive engines and their critical components.

Engine Development: In addition to the major effort on double acting V-type engines for medium duty automotive service, work is also proceeding on: one-cycle, two-cylinder engines for auxiliary systems, engines with indirect heat supply utilizing heat pipe technology, and engines with unconventional heating systems for underwater vehicle applications. Thus, in addition to automobiles, installations include generator sets, boats, and buses.

Engine design philosophy is to:

- Retain established I.C. engine technology whenever applicable for drive mechanisms and amplifiers.
- Concentrate development and production adaptation efforts on components which are vital for the Stirling process; ie. heat exchangers, piston rod seals, and power control.

Present main development program is on a double acting V-4 engine (Figs. 12, 13, 14, 15, 16). Three generations of this engine have been designed and built to date. The latest unit (Fig. 15), 60 hp, is to be installed in a Ford Pinto car under contract with the Ford Motor Company.

Components: The above figures also show the major components. It should be noted that the cylinder block and crankshaft drive system represent conventional I.C. engine technology. A relatively standard combustion air blower is used. A single burner serves all four cylinders. The heater head and regenerator are more closely akin to gas turbine technology.

The piston rod seal is a critical component which must withstand a pressure difference of about 2,000 psi above the atmospheric crankcase pressure. A sliding seal approach seems to be the best to date to have undergone a 4,000 hour endurance test. The potential life is expected to be twice this number. Piston rod seal test rigs simulate engine pressures, temperatures, and speeds as well as the lubricant and working fluid properties.

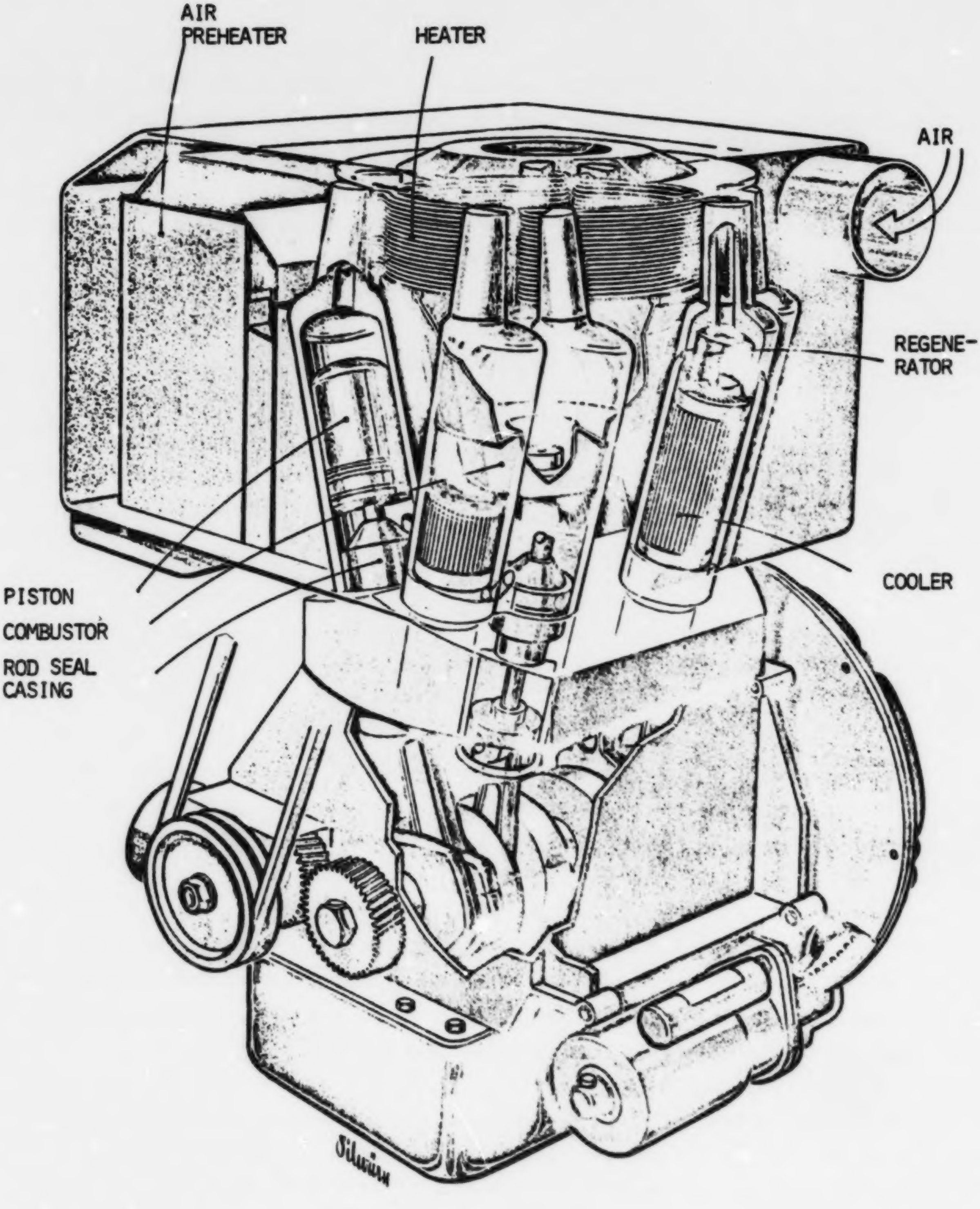

AIR PREHEATER
HEATER
AIR
REGENE-RATOR
COOLER
PISTON
COMBUSTOR
ROD SEAL CASING
Silvain

Fig. 12 Pre-Prototype, Dougle-Acting V4 Stirling Engine (First Generation)

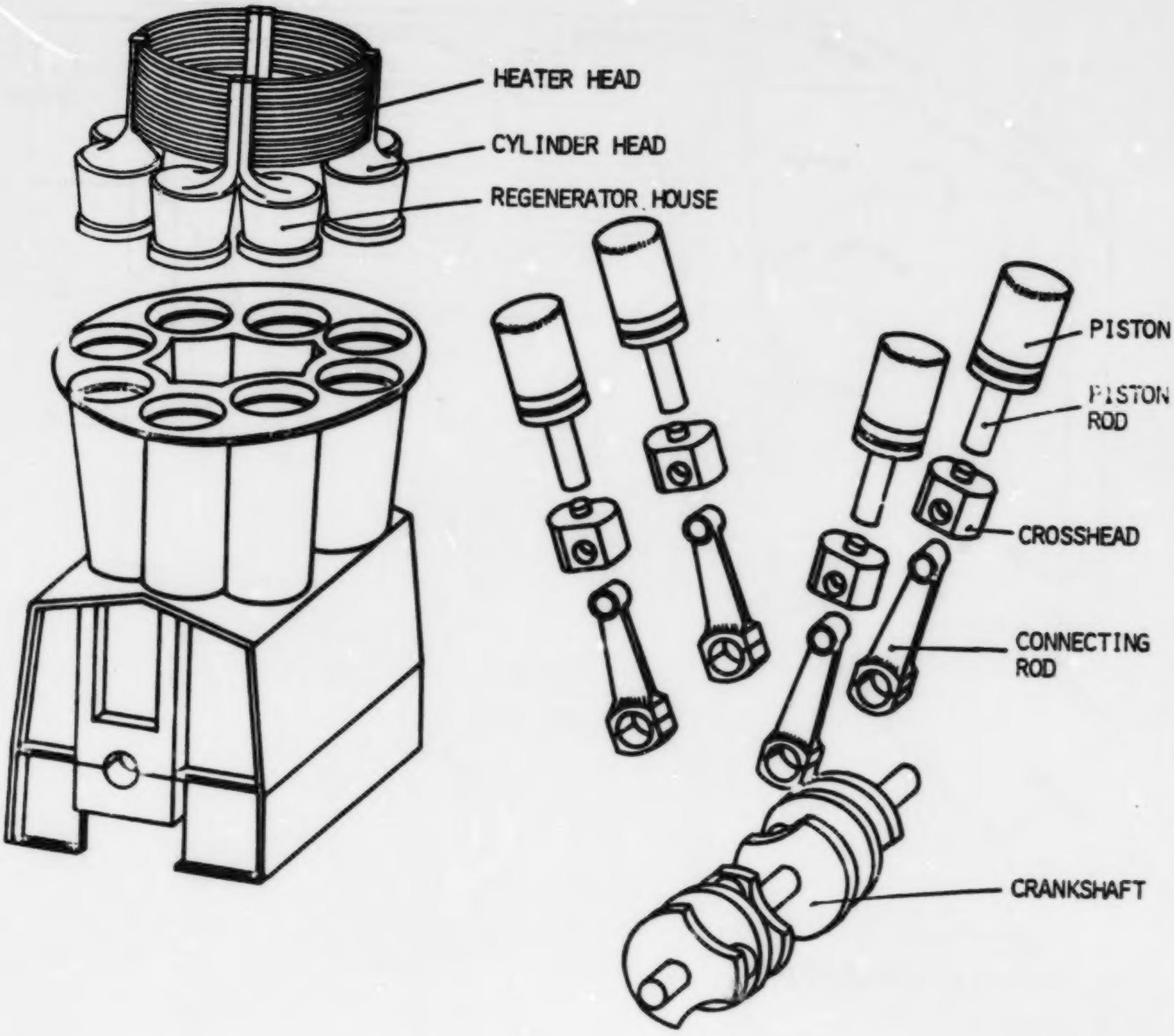

HEATER HEAD
CYLINDER HEAD
REGENERATOR HOUSE
PISTON
PISTON ROD
CROSSHEAD
CONNECTING ROD
CRANKSHAFT

Fig. 13 Exploded View of Dougle-Acting V4 Stirling Engine (Main Components)

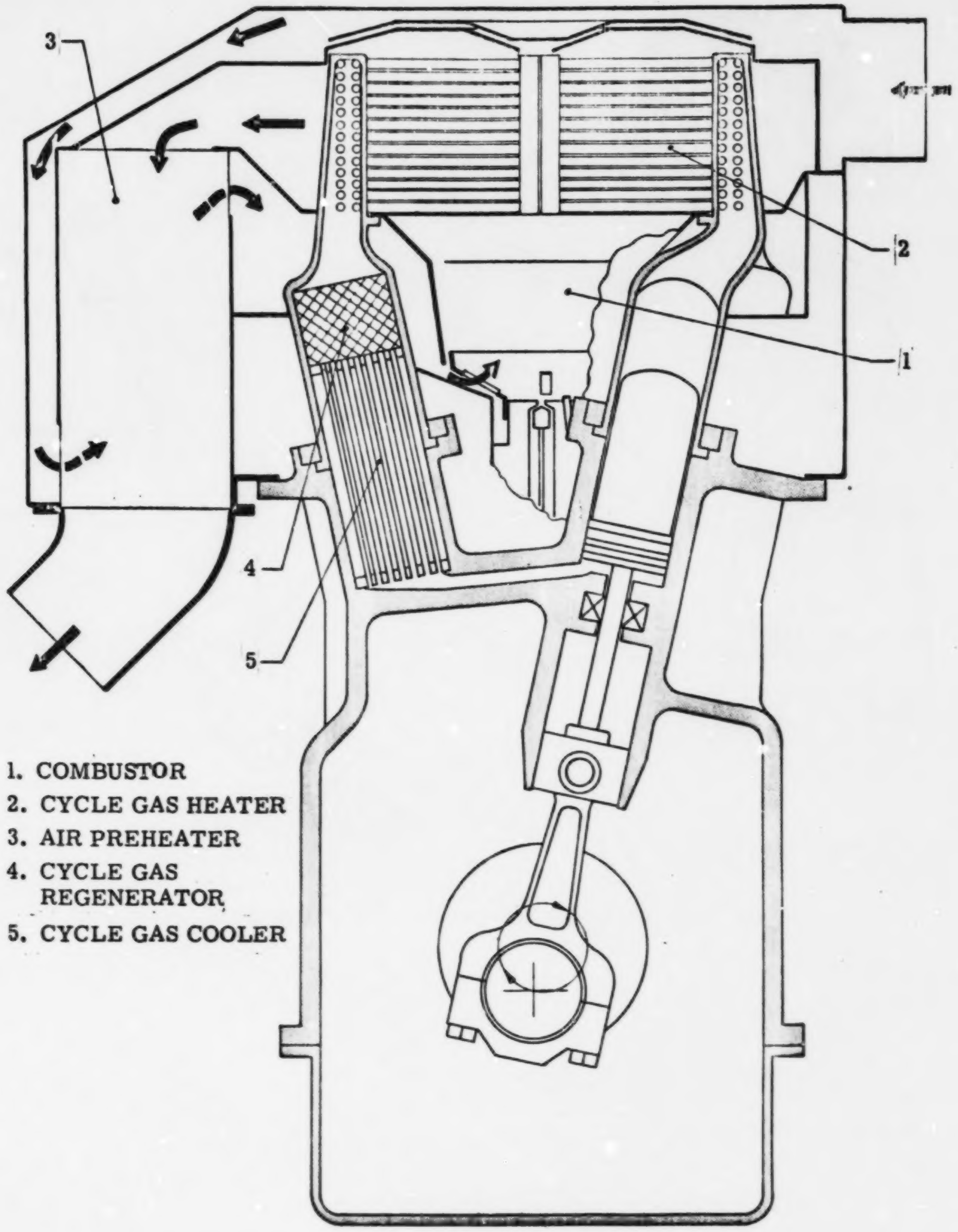
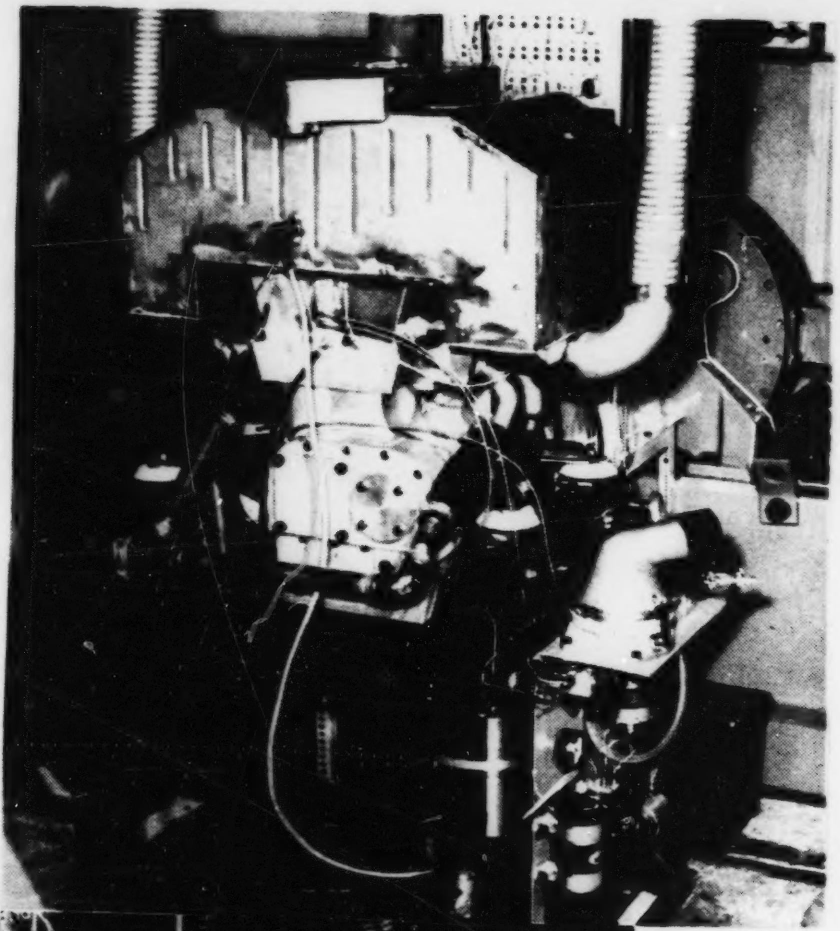

3
2
1
4
5
1. COMBUSTOR
2. CYCLE GAS HEATER
3. AIR PREHEATER
4. CYCLE GAS REGENERATOR
5. CYCLE GAS COOLER

Fig. 14 Cross-Section of Double-Acting V4 Stirling Engine

Figure 15

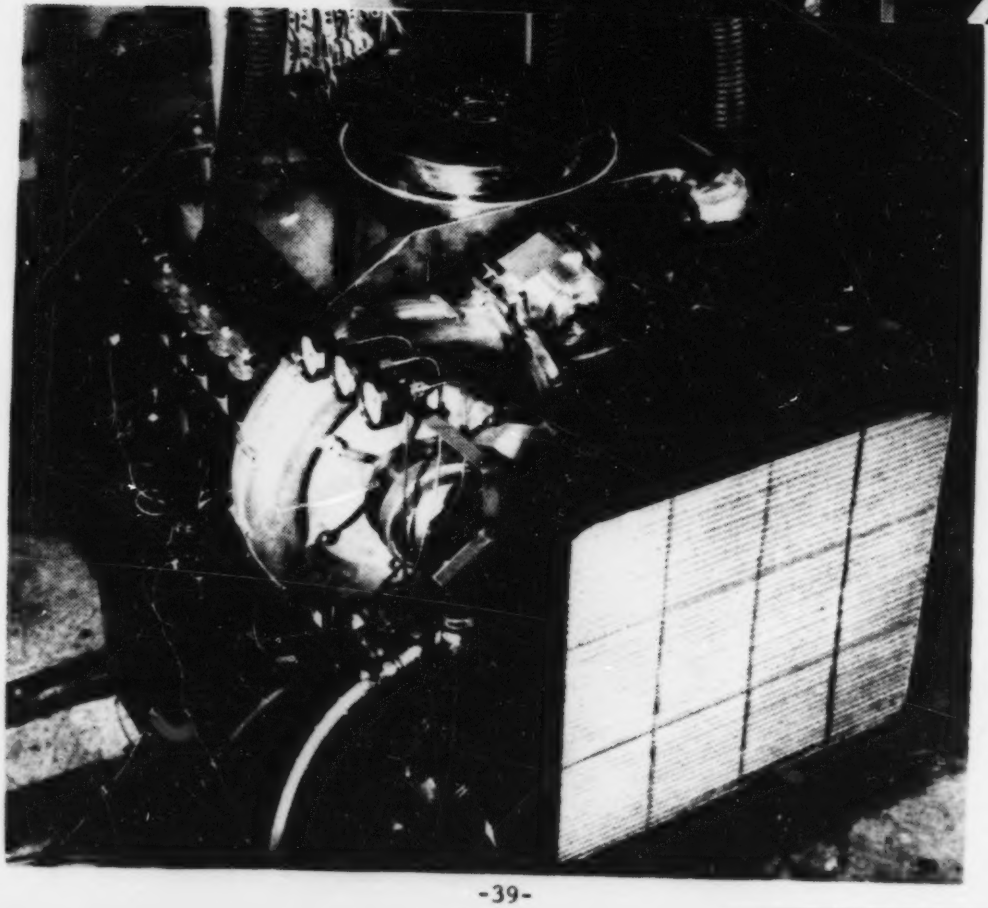
RIGHT:

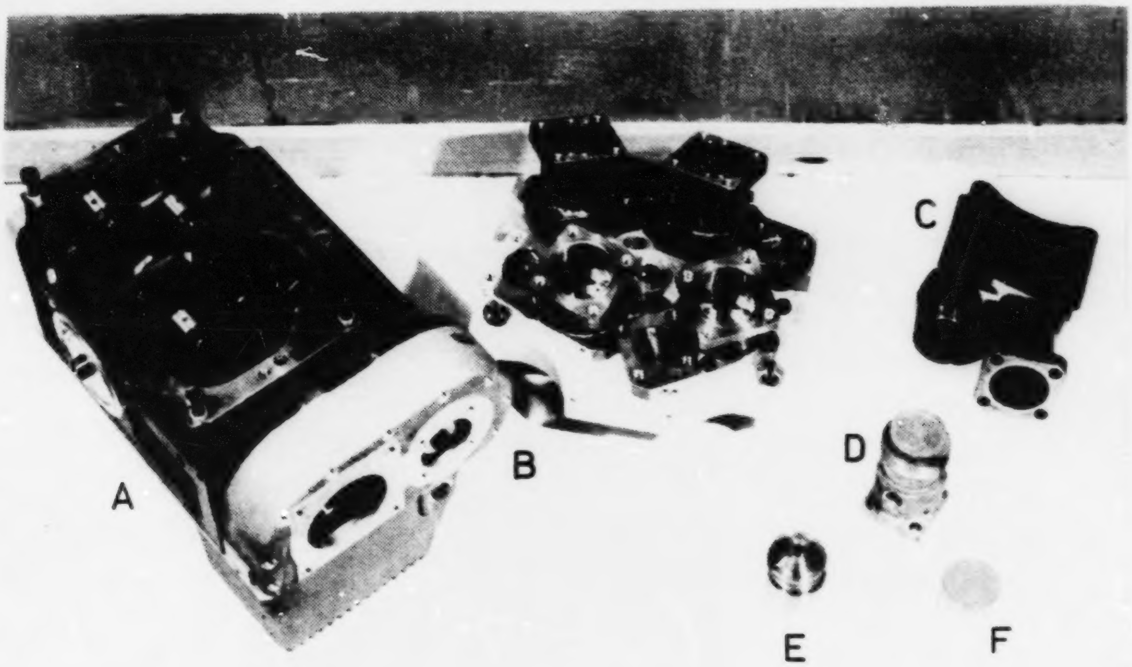
PRE-PROTOTYPE DOUBLE-ACTING V4 ENGINE ON THE TEST STAND



BELOW:

PRE-PROTOTYPE AUTOMOBILE POWER UNIT COMPRISING 3RD GENERATION V4 ENGINE





A	Crankcase
B	Cylinder block, cylinder liners
C	Heater head
D	Cooler
E	Piston rod seal unit
F	Regenerator

Fig. 16 Components of a Double-Acting V4 Stirling Engine

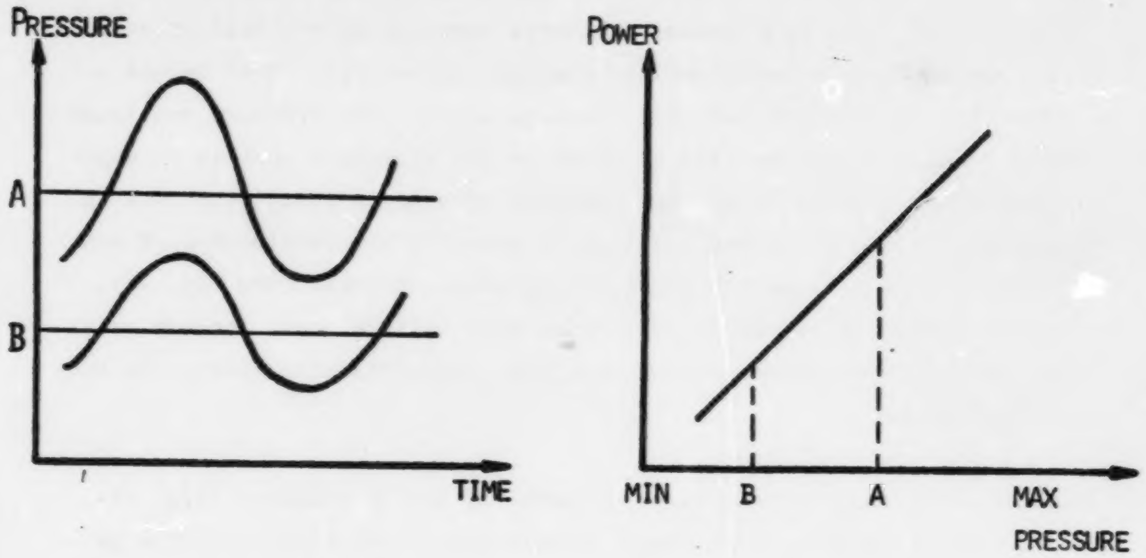
Two different basic control concepts for Stirling engines are illustrated in Fig. 17: mean pressure control and the pressure amplitude or dead volume control. The mean pressure control involves an external pressure vessel and a control compressor for pumping the working fluid in and out of the cycle to regulate its mean pressure level. The pressure amplitude control is less well-known and is based on the principle that an increase in dead volume results in a power increase with an insignificant loss in efficiency. Although United Stirling is pursuing the development of both concepts, emphasis is on the pressure amplitude approach (See Fig. 18). Step-wise change in volume in accordance with vehicle power demands seems to be the best compromise between cost and complexity of a continuous control function.

Obviously the engine incorporates a number of heat exchangers (Fig. 19). Whereas the air preheater is based on well-known technology from the gas turbine development, the cycle gas heater or heater head represents a technology with specific Stirling process requirements. Hence this component is getting a large percent of development attention.

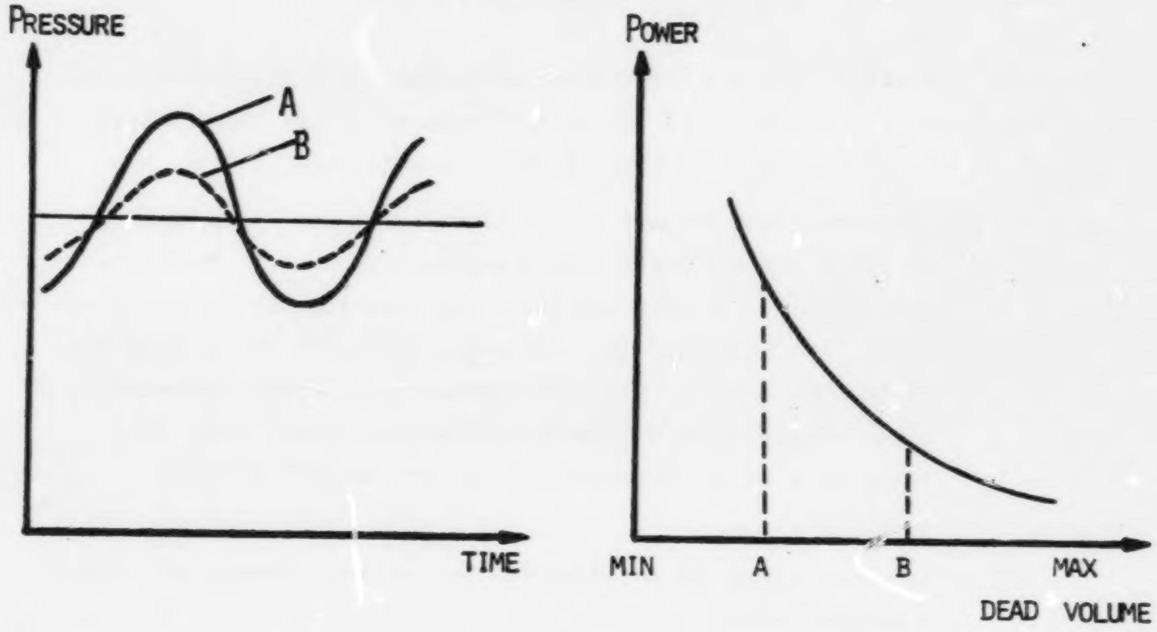
The heat pipe concept offers significant advantages in a Stirling engine. Its use is being developed with the partial support of the Swedish Board for Technical Development. Objectives of the program are to:

- Increase power density of the Stirling engine by increasing engine speed and still retain engine efficiency. This is a consequence of a very efficient heat transfer in the condensation end of the heat pipe, allowing an engine design with reduced flow losses. Rig tests showed a 10 percent increase in power density over a conventional heater head. (Fig. 20). There is a large potential for further power increases.
- Increase flexibility in choosing a heat source which may use gaseous, liquid or solid fuel. Use of heat storage is another possible choice.
- Increase engine efficiency by reducing temperature difference between the metal walls and the working fluid.

CONCEPTS OF STIRLING ENGINE POWER CONTROL



MEAN PRESSURE CONTROL



PRESSURE AMPLITUDE OR DEAD VOLUME CONTROL

Fig. 17 Concepts of Stirling Engine Power Control

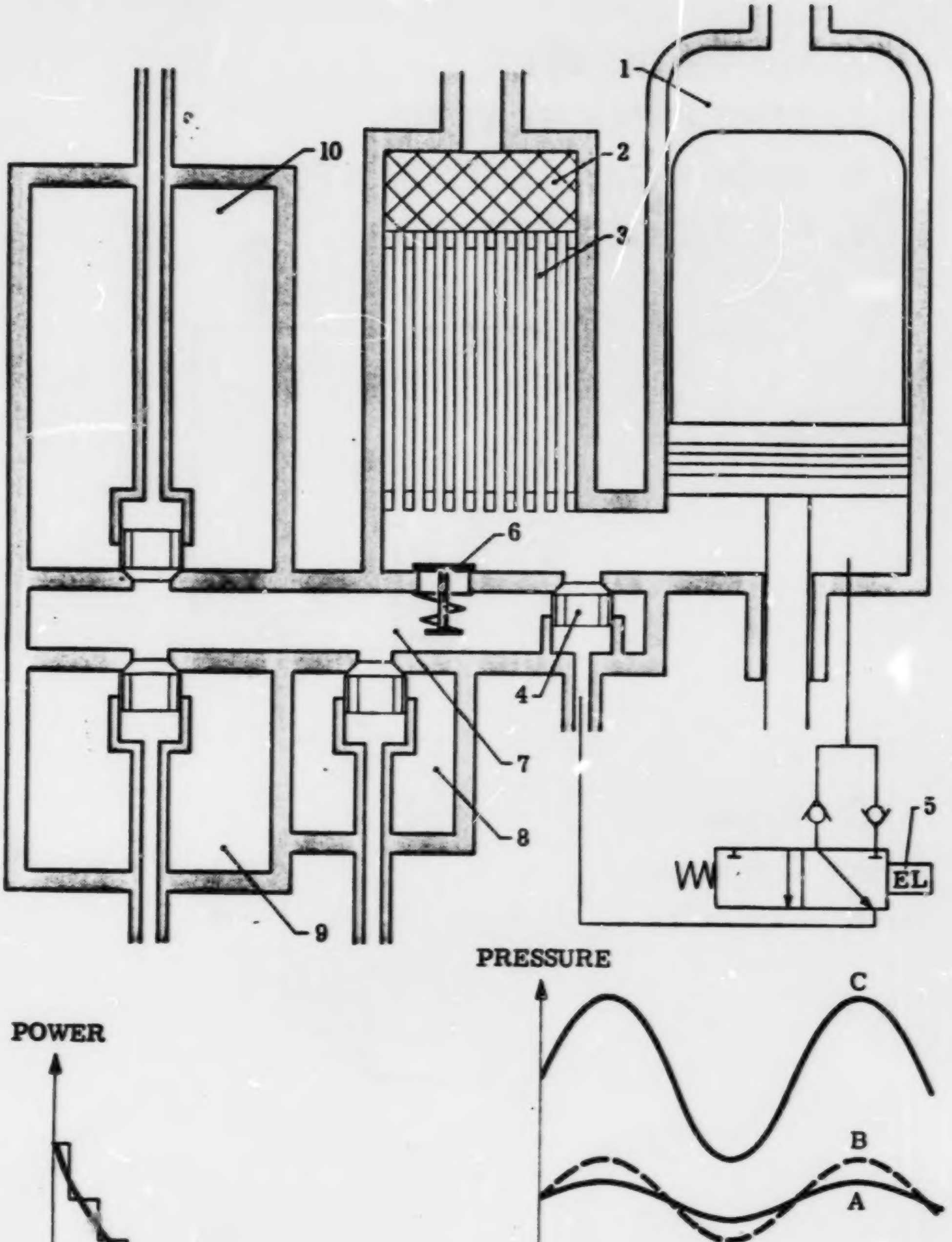

1
10
2
3
6
4
7
8
9
5
EL
PRESSURE
C
B
A
TIME
POWER
DEAD VOLUME

Fig. 18 Power Control by Means of Pressure Amplitude Variation

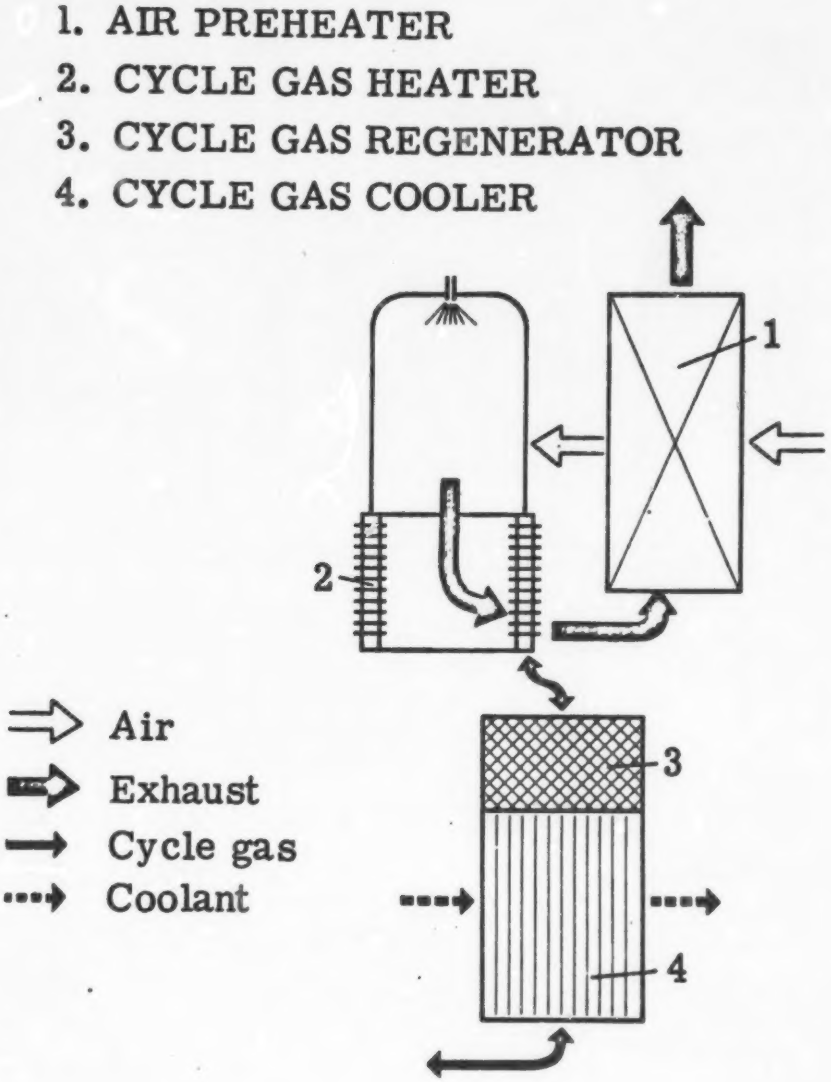
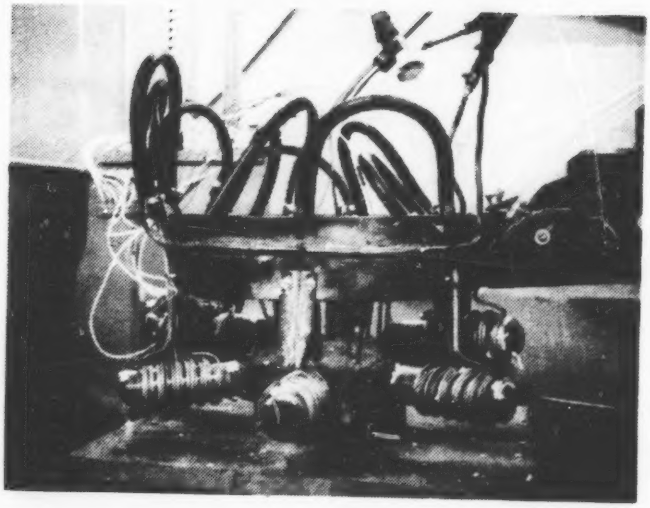

1. AIR PREHEATER
2. CYCLE GAS HEATER
3. CYCLE GAS REGENERATOR
4. CYCLE GAS COOLER
1
2
3
4
⇨ Air
➡ Exhaust
→ Cycle gas
⇢ Coolant

Fig. 19 Heat Exchangers of a Stirling Engine



Experimental test set up showing star-shaped heat pipe arrangement. In this feasibility phase, heat was supplied from a highfrequency generator (Left).
A second phase includes the integration of a low-emission combustor and a heat pipe.

Fig. 20 Indirect Heating by Means of Heat Pipes — An Example of Advanced Component Research

- Further reduce exhaust emissions due to more flexibility in choosing the combustor layout.

A second phase of the program which is currently in progress will integrate a low emission burner, a heat pipe, and a V-4 dougle acting engine into one system. A weight-to-power ratio of the oder of 2.5 kg/kw is anticipated.

Emissions, Weight, and Efficiency Characteristics: Emission characteristics of the Stirling engine are compared in Fig. 21 with 1975 and 1977 standards for both the California 13-mode cycle and the CVS vehicle test procedure. Even without exhaust gas recirculation (EGR), the Stirling engine is way below the standards, except for NO_x which is only 50 percent above the very stringent 0.4 gms/mi of the CVS procedure. EGR preliminary tests indicate that NO_x levels of about 0.2 gms/mi will be achieved with an insignificant loss of efficiency.

The high efficiency of the Stirling engine compared to alternative heavy or medium duty engines is shown in Fig. 22. The projected Stirling engine should be as efficient as the Diesel engine.

The power density of the Stirling engine is shown to be comparable to that of Diesel engines. (Fig. 23).

Noise Characteristics and Impact on Overall Vehicle Noise: The Stirling engine noise characteristics as compared to those of a Diesel engine are shown in Fig. 24 for the same general noise sources. This indicates some of the reasons why the enclosed cycle Stirling engine is an inherently quiet engine. The elements which do contribute to the noise of a Stirling engine are:

- The gears transmitting crankshaft torque (displacer type engines only)
- The combustion process
- Combustion air fan

○ CALIFORNIAN 13-MODE ENGINE TEST PROCEDURE
(DATA IN g/hph)

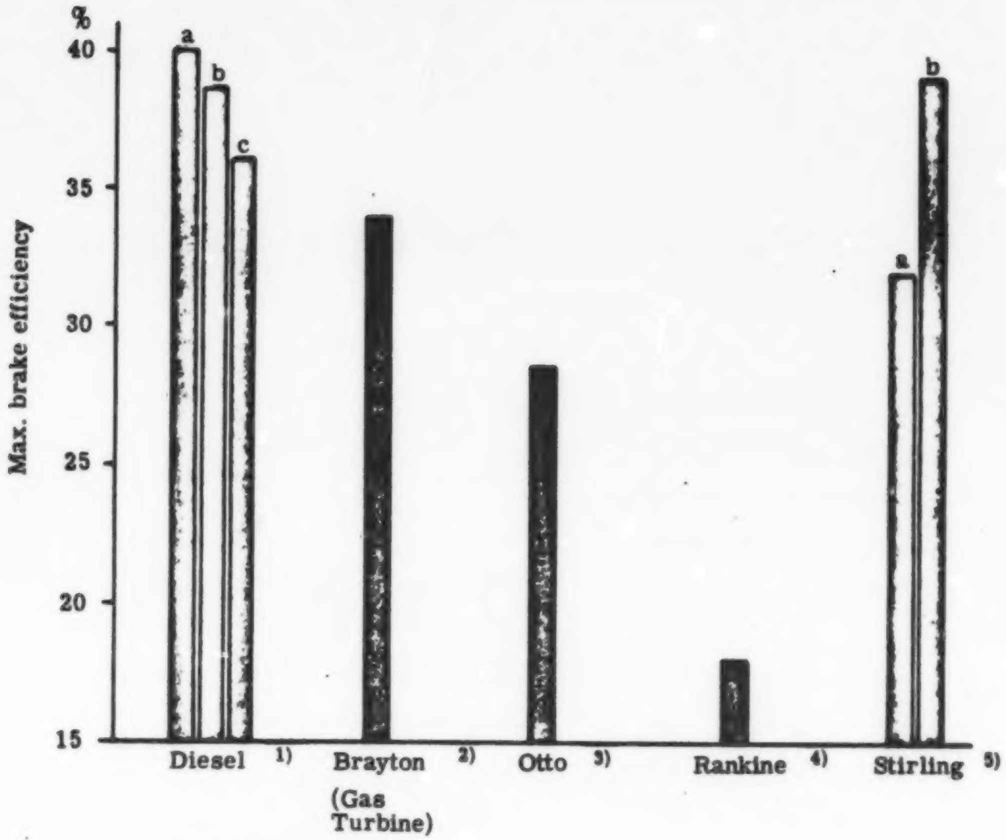
	NO_2 + HC	CO
1975 STANDARD	5	25
UNITED STIRLING V4 DOUBLE-ACTING ENGINE (WITHOUT E.G.R.)	2,1	1,1

○ C V S VEHICLE TEST PROCEDURE

(SIMULATED DATA IN g/mile, BASED ON ENGINE MEASUREMENTS)

	HC	CO	NO_x
1977 STANDARD	0.41	3.4	0.4
UNITED STIRLING V4 DOUBLE-ACTING ENGINE (WITHOUT E.G.R.)	0,1	0,9	0,6

Fig. 21 Exhaust Emissions — Summary of Measured Data



1) Typical 1972 figures:

a Turbocharged D. I. engine
b Normally aspirated D. I. engine
c " " I. D. I. engine

2) Average of 1972 regenerative gas turbines.
(Motortechnische Zeitschrift, Sept 1972, p 362)

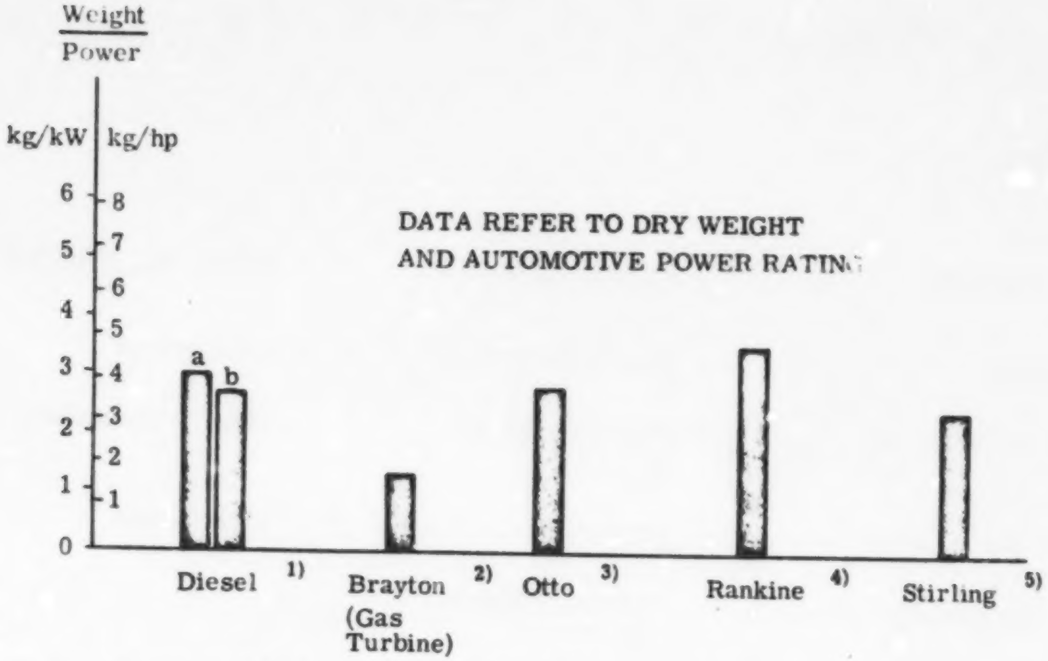
3) 1970 model according to General Motors

4) Bus engine, according to U. S. A. Dept of Transportation,
Steam Bus Symposium Proceedings, 1971.

5) United Stirling data:

a Pre-prototype engine measurement
b Projected for production engine

Fig. 22 Efficiencies of Alternative Heavy/Medium Duty Engines
(Effects of Emission Reducing Modifications Not Taken Into Account)



1) Average of typical, automotive engines around 150 kW

a Normally aspirated
b Turbocharged

2) Regenerative turbines. Average of existing 210-330 kW engines. Figures exclude air filter.

3) Average of typical automotive engines around 150 kW.

4) Bus engine, according to U. S. Dept of Transportation, Steam Bus Symposium Proceedings, 1971

5) Data refer to actual data of pre-prototype double-acting V4 engine.

Fig. 23 Weight-to-Power Ratios for Alternative Heavy/Medium Duty Engines

NOISE SOURCE	DIESEL ENGINE	STIRLING ENGINE
Combustion	Intermittent	Continuous
Pressure variation in cylinder	High pressure gradient	Near - sinusoidal
Aerodynamic flow	Intermittent	Continuous
Valve mechanism	Valves, rockers, tappets	-
Fuel injection	Intermittent High pressure	Continuous Low pressure

Fig. 24 Noise-Generating Mechanisms of Diesel and Stirling Engines

Noise measurements on a first generation double acting pre-prototype V-4X engine are shown in Figs. 25 and 26. These measurements were made one meter from an unsilenced engine with all auxiliaries which make a significant contribution to overall noise fitted.

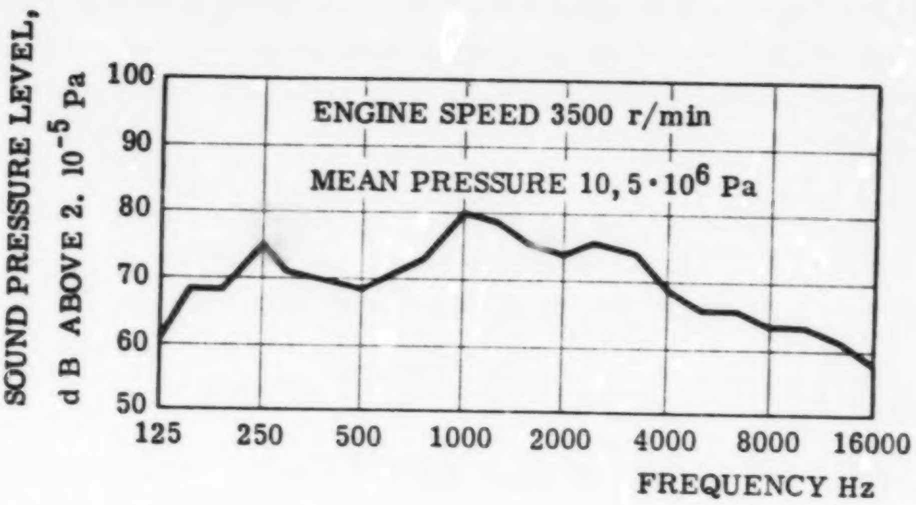
More important is the effect of the Stirling engine on the overall sound level of the vehicle. Two vehicle noise procedures are referenced: ISO R362 (used mostly in Europe and for the balance of this write-up) and the SAE J366 Procedure, (main difference is that the microphone distance for the SAE procedure is about twice that for the ISO procedure).

The progression of noise emission standards with time for commercial vehicles is shown in Fig. 27, with the 1988 California Code by far the most stringent to date. Measurements on an MAN bus with a Stirling engine (65 kw at 2700 rpm, displacer type, 4 cylinder in-line) installed show the overall noise to be 75 DBA - slightly less than the 1988 California Code.

Noise reduction in a truck is generally considered more difficult than in a bus due to inherent noise suppression associated with the installations. To date, however, no Stirling engine has been installed in a truck. A prediction for a truck, based on experimental data from the engine, is shown in Fig. 28. It appears that the 1988 California Code can be satisfied; however, it may be that the engine may not be the limiting or most noisy element of the entire truck system. Noise emissions from production engines are expected to be lower than those of the current pre-prototype engines.

Points Clarified during Question/Answer Period

- The control system is based on components which are more or less commercially available.
- The start-up cycle is comprised of a warm-up period (fuel and air supplied to engine) followed by a cranking impulse to the crankshaft when the cylinder head temperature reaches a level which will assure self-sustained operation. The start procedure takes about 20 seconds.
- Key problems involve reduction of manufacturing cost, For example, the heater head is made of high temperature material and is a high cost item. Many problems have come up in the course of proving engine durability.



Third octave band analysis of a first generation pre-prototype V4X engine (30 kW at 3. 500 r/min)

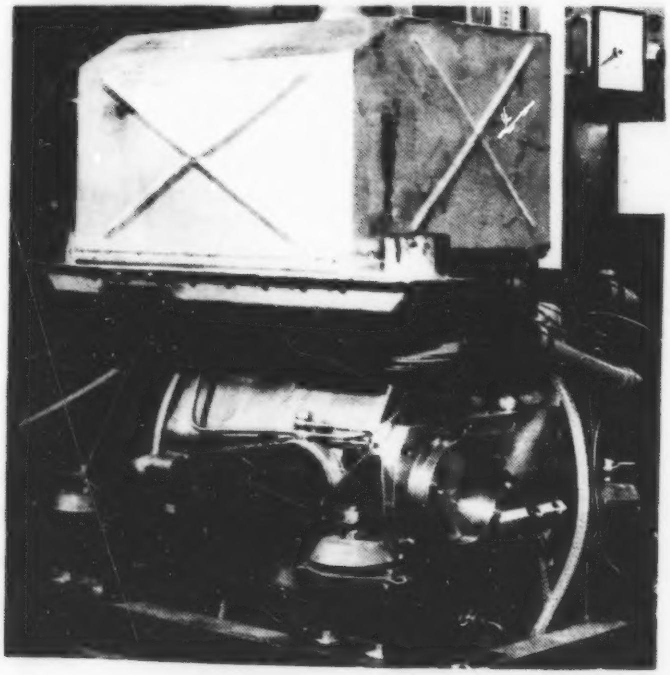


Fig. 25 Noise Measurements on a V4 Double-Acting Engine

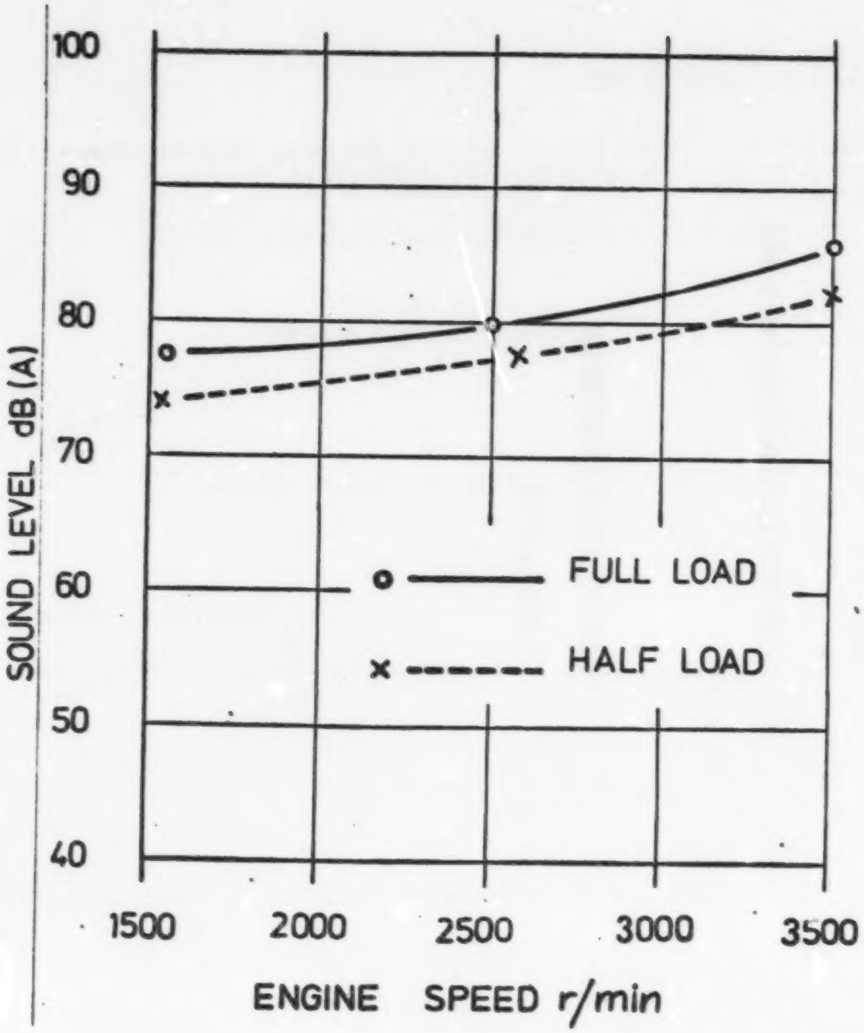


Fig. 26 Sound Level Versus Speed and Torque for the Stirling V4X Engine

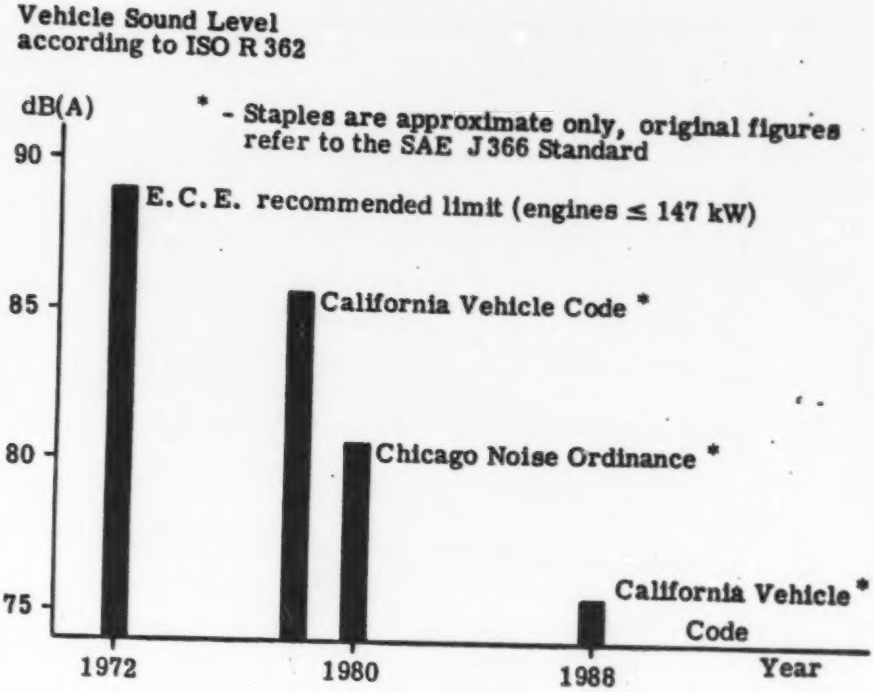


Fig. 27 Automotive Noise Emission Standards (Commercial Vehicles)

COMPONENT	dB (A) AT 1 METRE	dB (A) AT 7.5 METRES		ISO R 362 SYSTEM SOUND LEVEL dB (A)
Stirling engine 150 kW at 2400 r/min	81 1)	63		
		70.8		
Radiator fan		70 2)		
			74.1	
Manual 5-speed gear box and differential gear		72 3)		75.8
Tyre-road		71 4)		

1) Projection, based on United Stirling test data

2) Predicted, based on data from U.S. D.O.T.

3) Estimate, based on chassis measurements

4) Rib tyres "C", concrete (U. S. D.O.T. Report OST/TST - 72 - 1)

Fig. 28 Influence of a Double-Acting Stirling Engine on a Truck Sound Level (ISO R 362)

- No production cost estimates were revealed since it is premature to analyze prototype and experimental engines from this viewpoint.
- Piston rod seals are critical components and therefore warrant development of alternative approaches. The seal mentioned is an alternative to the roll-sock seal. Much of the design detail and the materials are held proprietary.
- Part load efficiency is good because operating temperatures are kept at a high constant level over the load range.
- Although it is conceivable that an infinitely variable control system might allow the transmission to be eliminated, this approach is not being pursued. The intent is to keep the system as simple as possible and to use standard components whereever possible.
- It is agreed that efficiency comparisons based on peak horsepower only may be misleading. With time and appropriate test data it is more significant to compare the efficiency or total energy required to cover a given or specified duty cycle such as the Federal Driving Cycle.

C. "Stage of Development of the Stirling Engine at the M.A.N." by Dr. P. Kuhlmann, M.A.N. - Augsburg, Germany

Stirling engine development at M.A.N. in Germany is summarized. A big share of M.A.N.'s production business comes from Diesel powered trucks and buses. Therefore, major attention is concentrated on how to propel these vehicles in the future when compliance with more stringent air pollution regulations will be required. Efforts toward solution to this problem involves the development of a number of different prime movers including:

- improved Diesel engine
- stratified-charge engine
- Stirling engine
- LNG-engine
- gas turbine
- electric drive

Predictions about which of these prime movers will power the vehicles in the future cannot yet be made. It depends on the results of the development work and also on the extra cost a country is ready to pay to avoid air pollution. But one thing is already clear: the Stirling engine has the potential to meet extremely difficult environmental requirements.

M.A.N. has been working on the Stirling engine since 1968, together with another German Diesel engine manufacturer, the Motoren-Werke Mannheim. Hence, the development team is supported by both the M.A.N. and M.W.M.. The first Stirling activity designed a single-cylinder engine developing 30 hp at 1500 rpm. All know-how and experience of Philips in the Stirling engine field was available through a license agreement. Several units were built; the first one was put on test in 1970. The 30 hp single-cylinder engine was improved constantly and is still being used for new engine component tests and scientific research.

Then a 4-cylinder Stirling engine developing 120 hp at 1500 rpm was designed and built with the same cylinder dimensions. The 4-cylinder engine is much more compact. This engine was put on test in 1972 and has been running very satisfactorily to date. The test runs demonstrated the excellent properties of the Stirling engine: clean exhaust, low noise level, and high efficiency.

Exhaust Measurements: The first measurements carried out in accordance with the 13-mode cycle gave the following results:

NO_x : 4.0 g/hph
CO : 0.7 g/hph
HC : 0.01 g/hph
Soot: 0 (Bosch Scale)

Except for nitrogen oxides, the concentration of pollutants is very low, even though steps have not yet been taken to modify the combustion system of these engines to achieve particularly good exhaust composition. The NO_x concentration can be reduced to less than 1 g/hph by design improvement and special modifications (exhaust gas recirculation for example). Because of its external combustion, EGR has no influence on the thermodynamic process of the cycle and consequently does not lower the engine output.

Noise Level: Fortunately, the good exhaust composition of the Stirling engine goes hand in hand with a low noise level. At the small distance of only 1 yard the noise level of the unshielded engine, measured at our test bed, was as low as 85 db (A), with the engine running under full load. That is about 20 db less than for Diesel engines. The noise of an installed Stirling engine is so low that the total noise of a vehicle is more determined by the auxiliaries, the tires and the body of the vehicle than by the engine itself.

Efficiency: Of importance, especially in view of the diminishing energy resources, is the high efficiency of the Stirling engine. The measured overall efficiency of the test engines is about 33%. Also very important is the high efficiency at part-loads. On the whole, the Stirling engine shows considerably lower fuel consumption than a gasoline engine.

Multifuel Capability: Another advantage of the Stirling engine is that it can be run on heat supplied from any heat source. That means that all liquid or gaseous fuels are suitable, ie. Diesel fuel, petrol without any lead, propane and natural gas as well as hydrogen,(a fuel that may become more important in the future). There is the possibility of running the Stirling engine with heat from a heat buffer in which case there would be no exhaust at all. The capacity of such a Stirling engine is many times higher than that of a lead battery of the same weight, used for electric drive.

With the advantages mentioned and other good properties of the Stirling engine, such as its good torque characteristics and low vibration level, the question arises, why then are not all road vehicles already equipped with Stirling engines. The answer is that reliable Stirling engines cannot be mass produced at an acceptable price today. The Stirling development team of M.A.N. and M.W.M. has undertaken the task to develop the Stirling engine so that it will be reliable and suitable for mass production at low prices.

At present it is not intended to build a Stirling engine for a certain application, but rather to improve the engine in general, particularly in those areas mentioned above. When this has been achieved, the engines can be easily adapted to particular applications, such as buses, generator sets or boats in accordance with current production programs of M.A.N./M.W.M.. Starting from the present engines, completely new engine components have been designed. Of particular importance are the heater head and the air preheater. These together with the burner chamber comprise the hot parts of the Stirling engine. The heater head is one of the most important components of the Stirling engine. It incorporates 3 heat exchangers: the heater, the regenerator and the cooler. Early designs performed well, but were not suitable for mass production because the amount of labor cost was too great. A new heater head was developed which is much simpler in production. It is made up of straight tubes, some smooth, some finned, but identical within each group. With the cylinders, which, for example, could be precision castings, and the 180° bends, also cast, the heater tubes are simply stacked together and are vacuum-brazed in one operation. The saving in labor cost is evident. Savings are also made in the cost of material by dividing the heater head into temperature zones. Thus the most suitable material for the respective temperature level can be used.

The air preheater transmits the exhaust heat to the combustion air to increase the efficiency of the Stirling engine. A tube and jacket type heat exchanger was used in the single cylinder engine. The very large number of tubes approximately 1500, raised production cost considerably. The latest version of the air preheater is a plate type. The plate pack is made by folding a sheet metal strip. This fold pack needs to be sealed only at both face surfaces. The cross sectional areas for the inlet and the outlet of combustion air and exhaust gas can then be very easily provided by a corresponding shape of the casing into which the fold pack is inserted.

Besides being favorable in cost and suitable for production, this air preheater has two more important advantages: the fold pack can expand freely when subjected to heat in operation so that no thermal stresses or cracks can occur; and the fold pack can be readily removed from the casing for maintenance or replacement, if necessary.

Efforts toward design simplification and reduction in cost also include the gear. The gear of the earlier engines, and of the displacer type, is a rather intricate rhombic gear consisting of many parts. In contrast, the new generation of multi-cylinder Stirling engines will be built using the double acting principle with the cylinders arranged in one line. Use of the double acting principle cuts the number of parts required per cylinder to about half, since there is only one piston per cylinder instead of two. The in-line arrangement permits a particularly simple construction of the gear. Furthermore, this design permits an engine type that will cover a wide power range just by varying the number of cylinders per engine.

Points Clarified during Question/Answer Period:

- Regarding the piston rod seal, the roll-sock seal has been used to date, but design and development effort is being devoted to alternative seals. So far, no better seal design has been demonstrated.

- The highest temperature in the engine is at the heater tubes; hence they need the best materials. Other lower temperature parts could use lower grade materials, matched to the temperature requirements.

- Regenerator has an efficiency of 99.9%. Because the time for storing and rejecting heat is short, very little heat is lost to the surroundings.

- Cooling system must reject 50% of the heat in fuel; hence the capacity of the cooling system must be about twice that for a comparable Diesel engine. This does not necessarily mean it must be heavier. The fan power will depend on the details of the design.

- Combustor inlet air is not filtered; the gaps in air preheater are a little larger than 1 mm.
- If a glass ceramic core is used for the air preheater, as Philips plans to do for the Ford Torino, then a conventional automotive air cleaner would be appropriate.
- Mean pressures and temperatures are 110 - 120 atmospheres (United Stirling is at about 150 atmospheres average pressure) and 630 - 650 degrees Centigrade, respectively.
- All three companies (Philips, United Stirling, and M.A.N.) are working with both helium and hydrogen as working fluids. Although the most generally accepted and preferred fluid is helium, there are strong performance incentives to use hydrogen. Also , leakage is a problem with hydrogen.
- There are plans to use hydrogen at 200 atmospheres in the Philips Ford engine. At high pressures the hydrogen diffuses into the walls. There are a number of safety questions to be answered. Test work at Stanford seems to allay these fears.
- High temperature heat exchangers exposed to flame must withstand high thermal stresses. Maximum hydrogen temperature inside the tube is about 650°C: combustion side temperatures reach 850°C. Hydrogen embrittlement of the materials has not been found.
- Maximum cycle temperatures are expected to go to about 750°C. It is limited by materials capabilities. At present the best gas turbine materials are being used.

III. GAS TURBINE ENGINES

A. Gas Turbine Development Overview by George M. Thur, Chief, Power Systems Branch, Alternative Automotive Power Systems Division, EPA

The purpose of the AAPS Program is to evaluate the feasibility of alternative power systems for automotive transportation. The approach is to develop the required technology, to demonstrate the feasibility in full-scale system tests, and to evaluate the relative potential of the most promising systems by analysis of the test results.

In addition to the objective of low pollution emissions, the incentives for improved fuel economy are rapidly increasing in importance. The trends shown in Figure 29 show that the Otto cycle engine modified for emission control will aggravate an already difficult fuel supply problem in this country by 1985. Five general approaches to alleviating this problem and their projected impact on the fuel crisis are shown. Items 3 and 4 are the concern of AAPSD in seeking to demonstrate alternate power plants with low emissions, improved fuel economy, multi-fuel capability and ability to use new or synthetic fuels. These may be required to turn the trend based on unmodified reciprocating internal combustion engines (RICE dashed line) while electric propulsion systems based on nuclear energy sources are emerging.

Average fuel economy curves from EPA certification test data are shown in Figure 30. About a 7% average penalty is associated with the emission controls on the 1973 cars as compared to the precontrolled 1957-67 cars. The test points on the left reflect the current capability of the engines shown. The points at 4500 lbs. weight represent the 1975 demonstration goals for the Rankine, Brayton and Stirling engines; the projected range for these systems in the 1977-1980 time frame is 17 - 19 mpg.

Thermal efficiency over the Federal Driving Cycle is shown in Figure 31 for various test engines as compared to the 1973 certification test data.

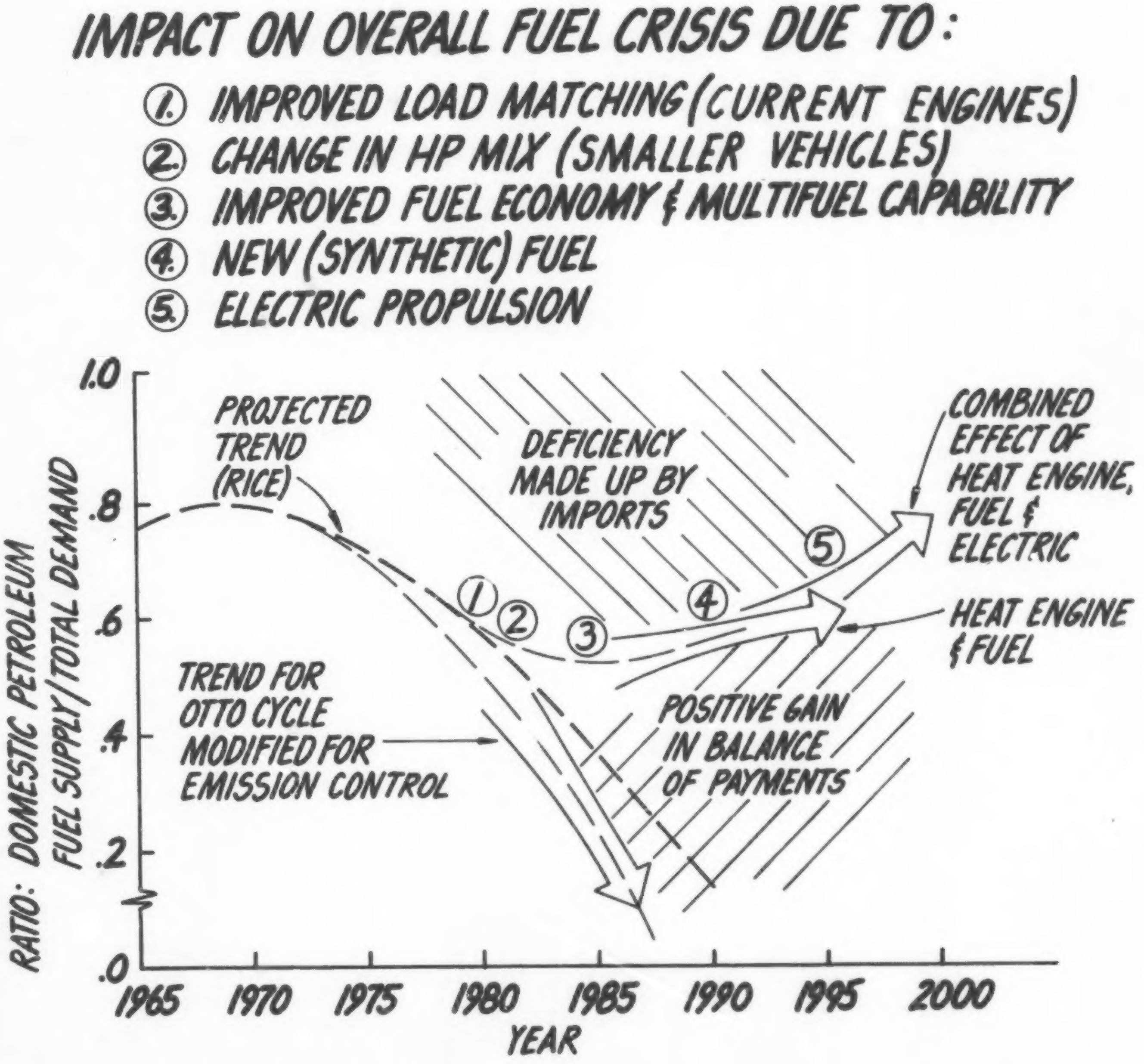


Fig. 29 Projected Trends and Factors Influencing Fuel Supply/Demand Ratio

FUEL ECONOMY OVER THE FEDERAL DRIVING CYCLE

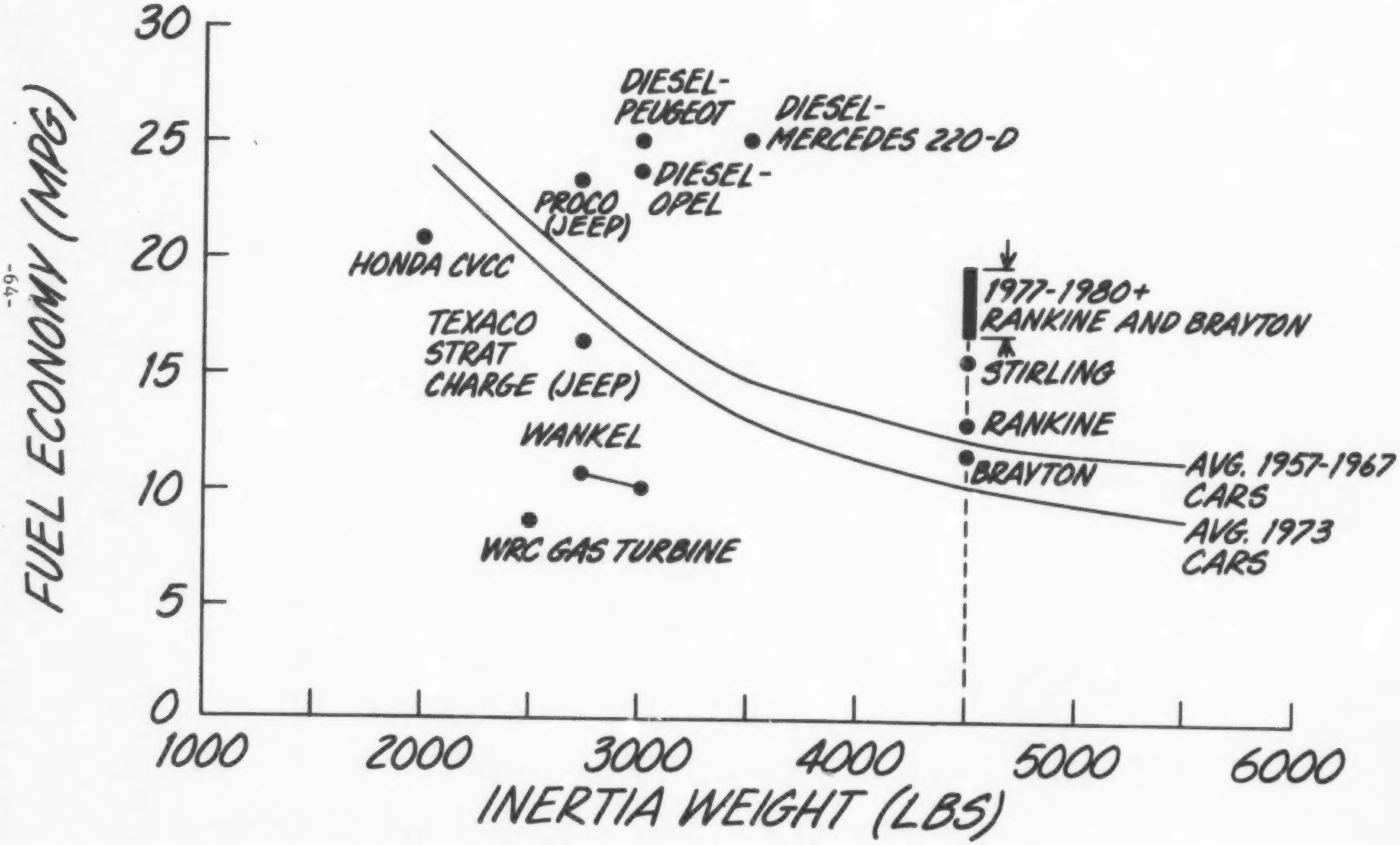


Figure 30

THERMAL EFFICIENCY OVER
THE FEDERAL DRIVING CYCLE

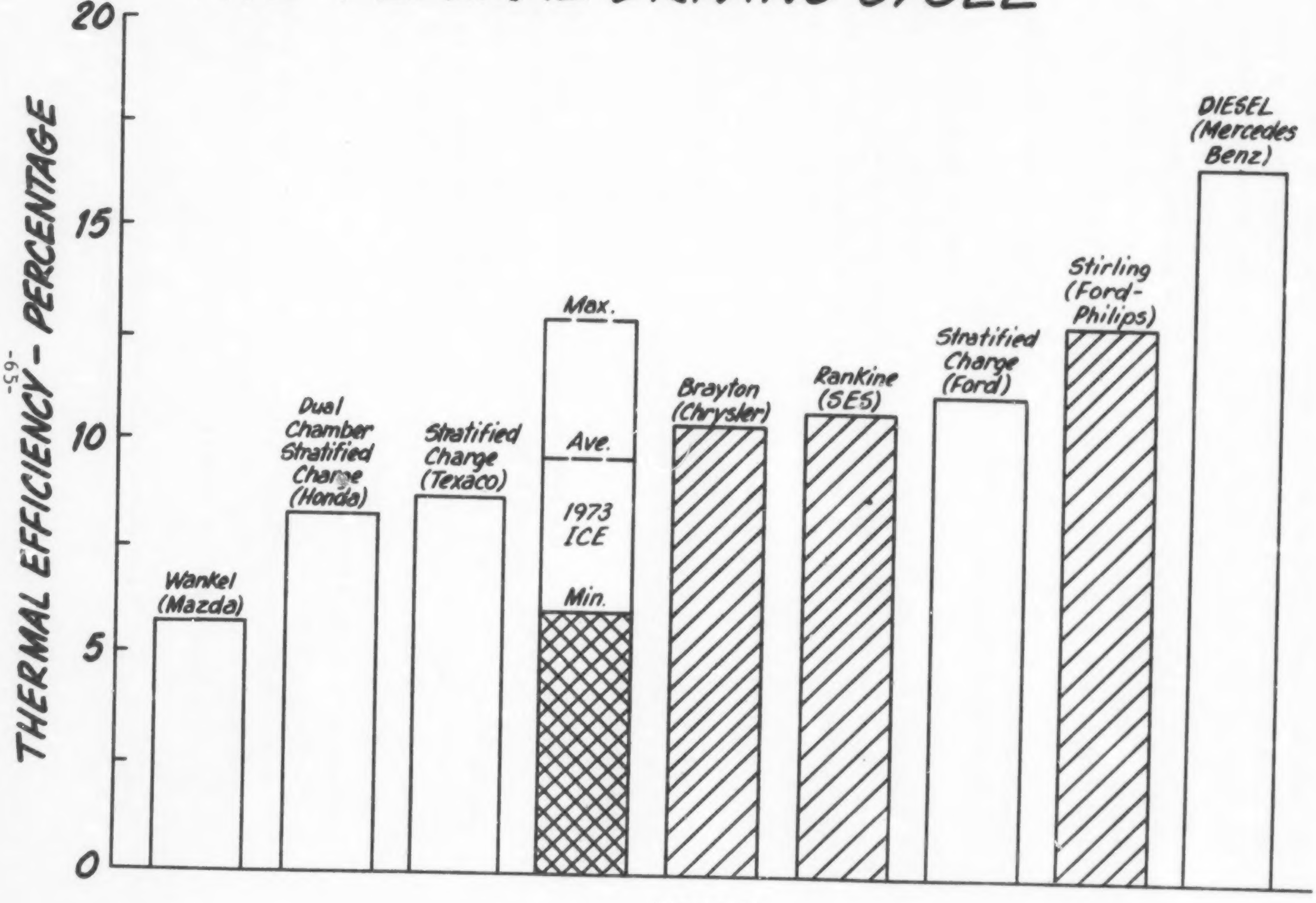


Figure 31

The AAPS Gas Turbine Program has two parts: technology and component development, and the Baseline Engine problem solution demonstration. A general breakdown of the tasks and schedule showing how the technology programs feed into and support the Baseline Engine Program is shown in Fig. 32. The intent is to demonstrate a practical gas turbine powered vehicle which satisfies the emission goals and the fuel economy goals by late 1975. The 1975 fuel economy goals and the 1980 projections are shown in Fig. 33.

B. Volkswagen Gas Turbine Research by Dr. W. H. Hucho, Fluid Mechanics Department, Volkswagen, Wolfsburg, Germany

Along with other alternative power systems, the Research Department of Volkswagen is investigating the gas turbine as a power unit with the potential of low exhaust emissions. The purpose is to develop a passenger car gas turbine with performance and production costs comparable to the spark ignition piston engine, but with improved exhaust emission characteristics. The development schedule is shown in Fig. 34.

Phase 1 was devoted to getting feasibility information on gas turbines for passenger cars in the very low power range and identifying the tasks for further development.

Based on the results of the first engine tests, further improvement of the layout and component problem areas were pursued along with selected compromises necessary to meet passenger car requirements (Phase 2). Special emphasis is being given to development of a low NO_x combustion system. Other work is aimed at reducing production costs by simplification of the two-shaft engine. Possible use of a single-shaft arrangement and increased temperatures, using ceramic turbine parts, is being considered.

If these developments continue to look promising, Phase 3 will be concentrated on questions of durability, manufacturing cost, etc. and should result in a pre-prototype car gas turbine.

Research Engine: The research engine developed with Williams Research Corp. is shown in Fig. 35. This is a two-shaft machine with regenerative air

GAS TURBINE POWER SYSTEM PROGRAM

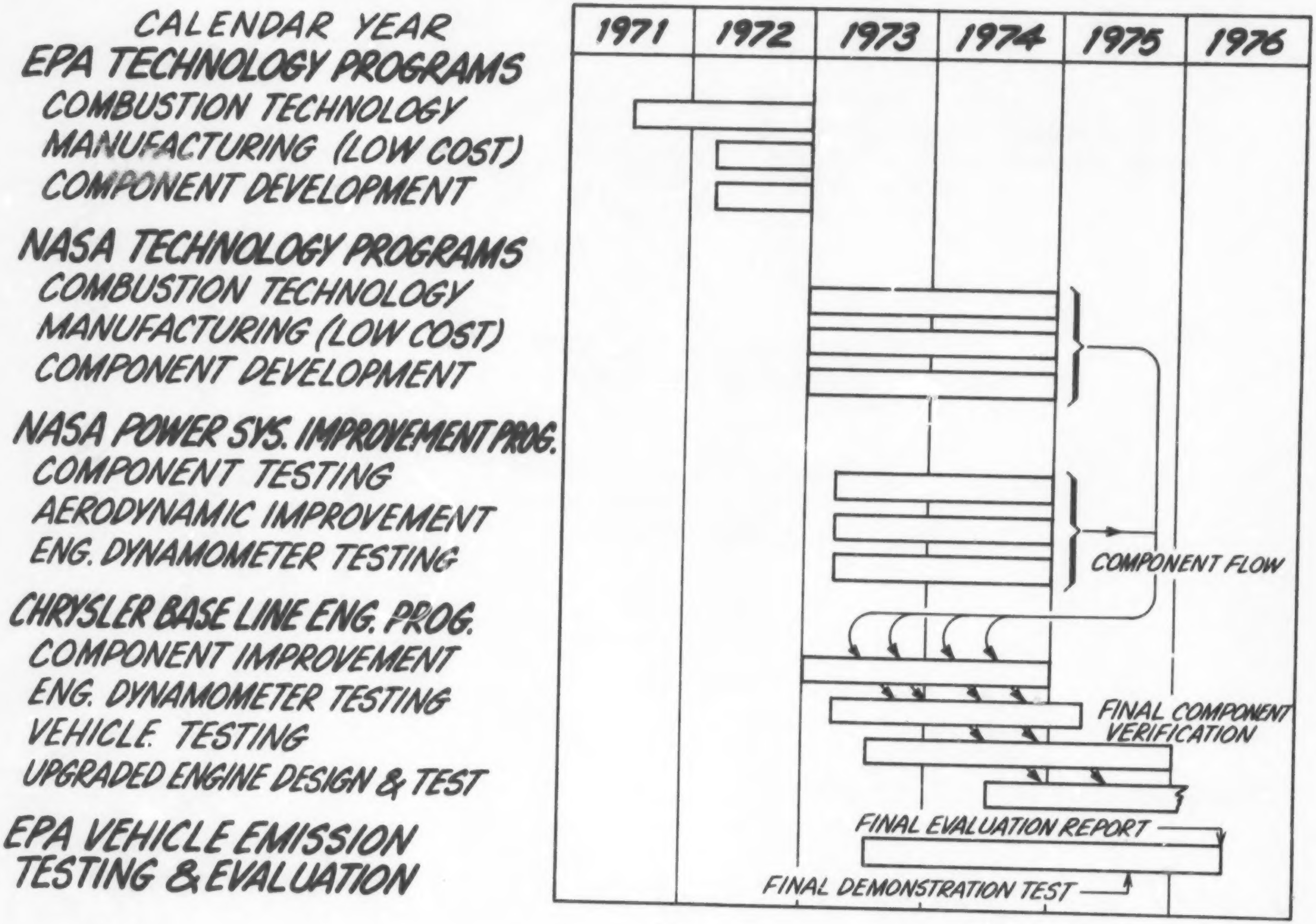


Figure 32

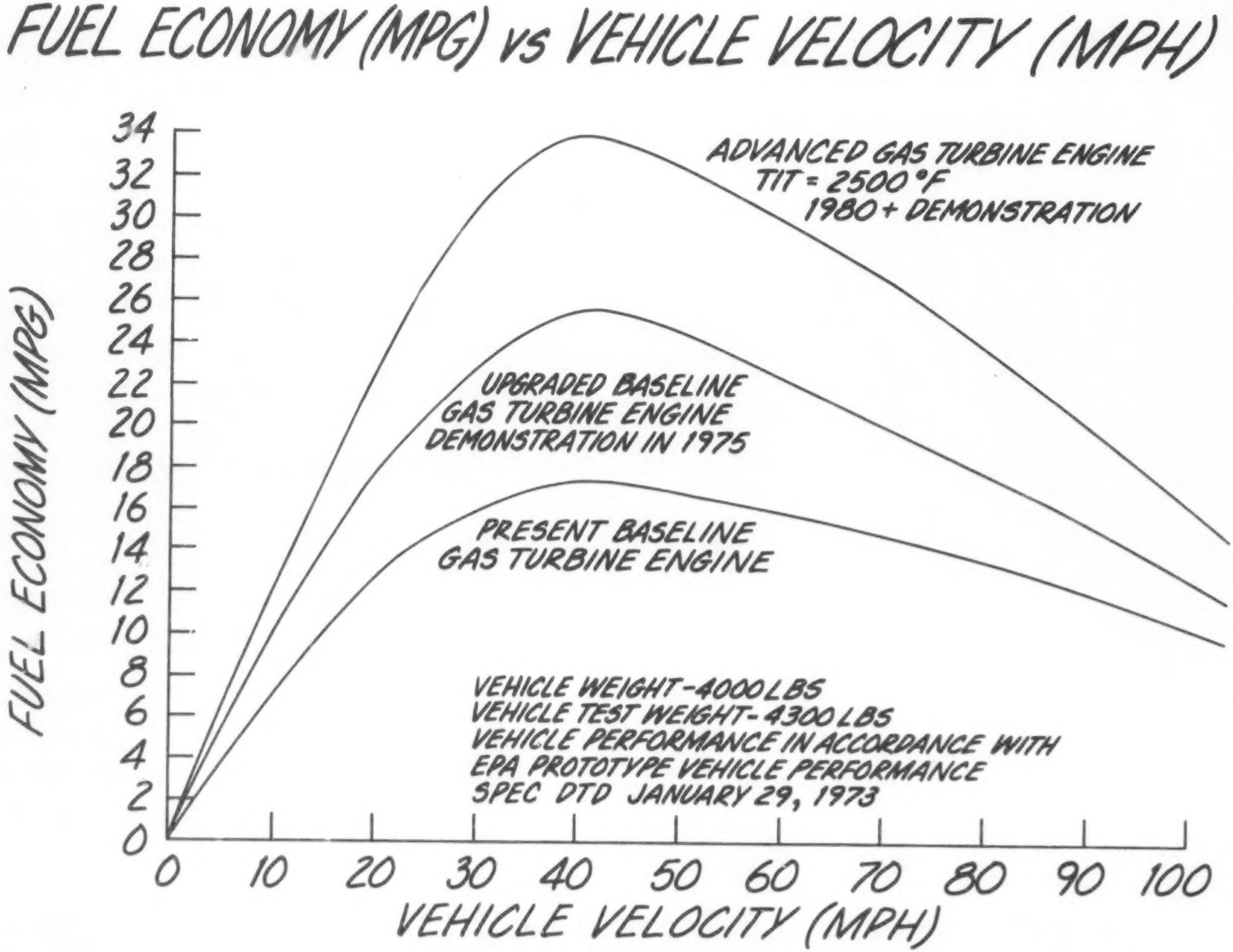
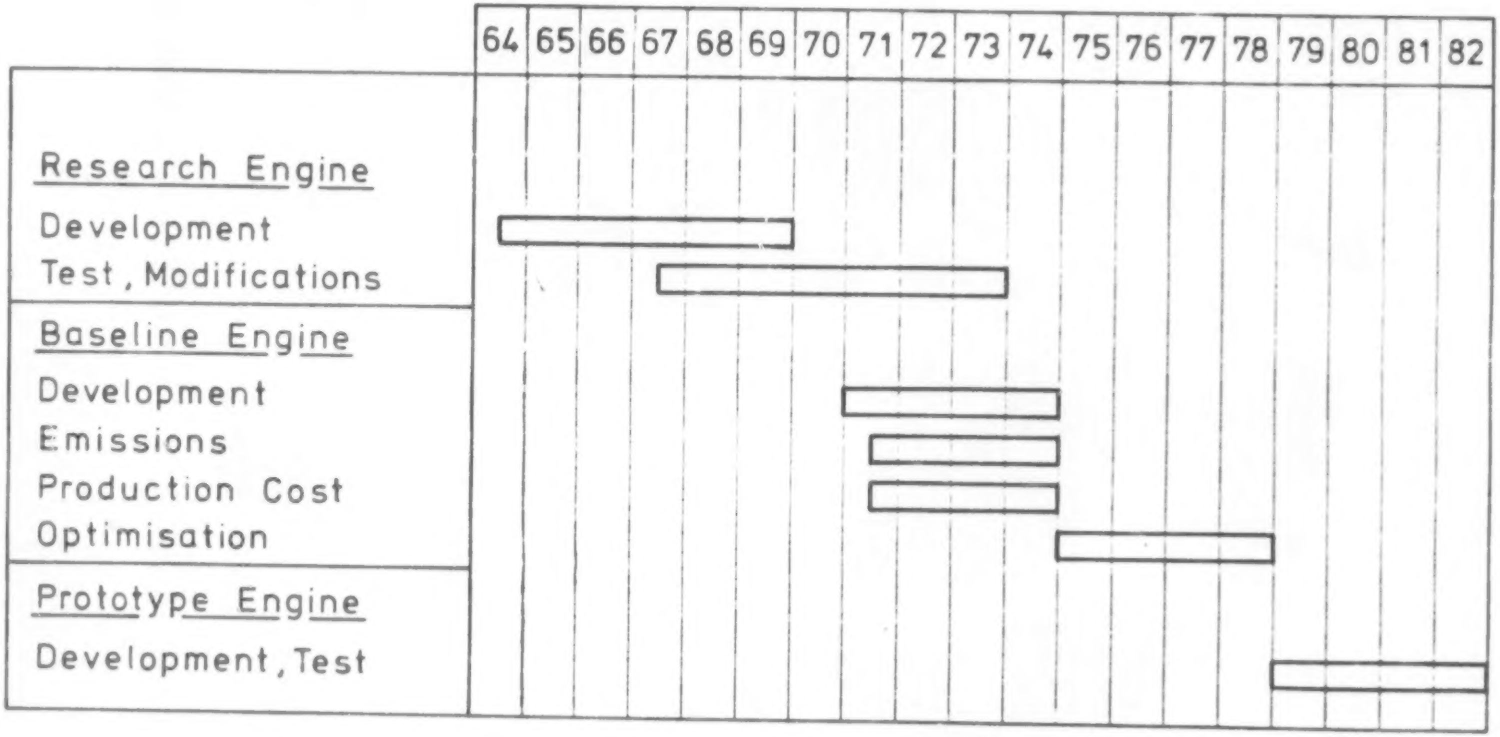

FUEL ECONOMY (MPG) vs VEHICLE VELOCITY (MPH)
FUEL ECONOMY (MPG)
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
10
20
30
40
50
60
70
80
90
100
VEHICLE VELOCITY (MPH)
ADVANCED GAS TURBINE ENGINE
TIT = 2500°F
1980+ DEMONSTRATION
UPGRADED BASELINE
GAS TURBINE ENGINE
DEMONSTRATION IN 1975
PRESENT BASELINE
GAS TURBINE ENGINE
VEHICLE WEIGHT - 4000 LBS
VEHICLE TEST WEIGHT - 4300 LBS
VEHICLE PERFORMANCE IN ACCORDANCE WITH
EPA PROTOTYPE VEHICLE PERFORMANCE
SPEC DTD JANUARY 29, 1973

Figure 33



Original VW-Gasturbine Program

Figure 34

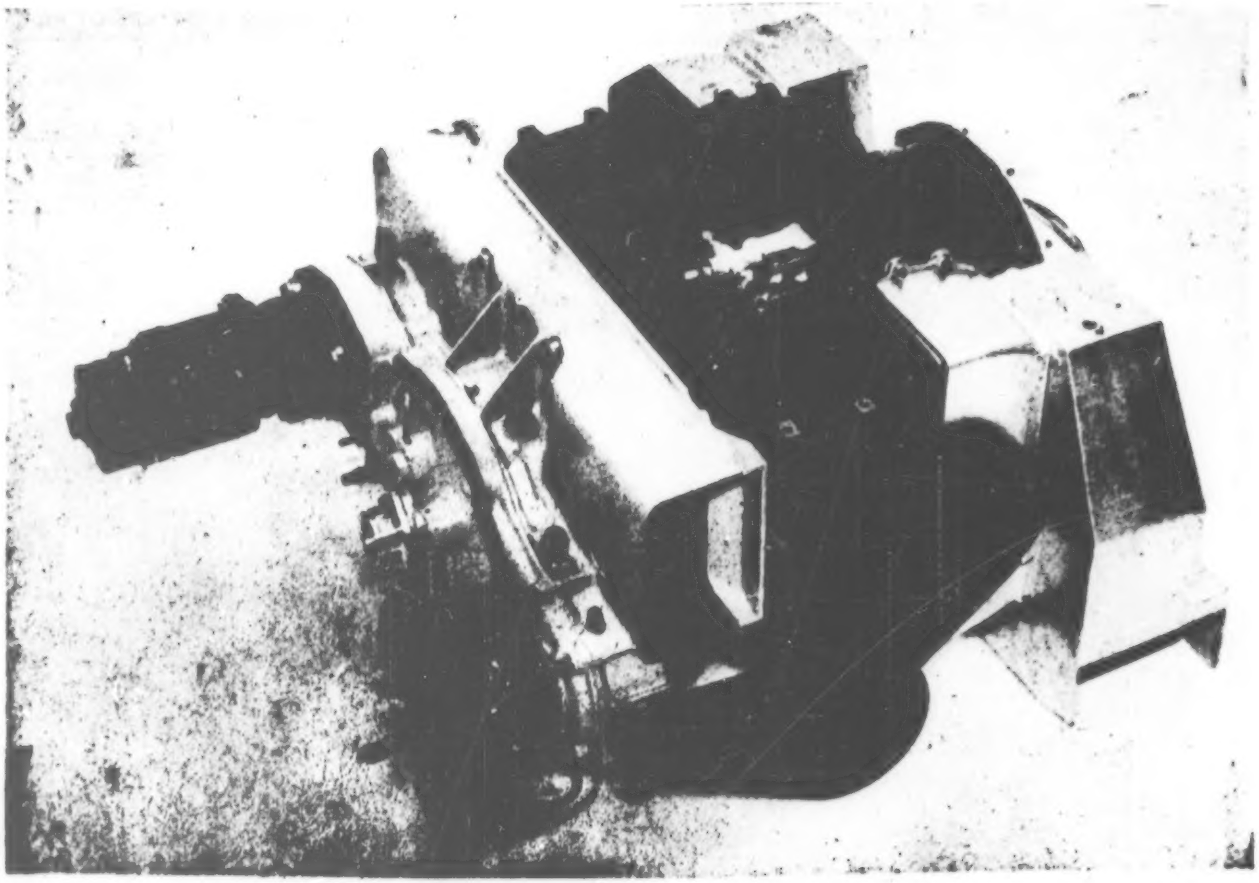


Fig. 35 Volkswagon Research Gas Turbine VW-GT 70

pre-heating and an integral reduction gear. This engine develops 75 hp and fits into the rear engine compartment of various Volkswagen vehicles. Some full power engine performance data are given in Fig. 36. The VW-GT 70 operates with a moderate turbine inlet temperature of 1674 F, a compressor pressure ratio of 3.6 and a heat exchanger effectiveness of 80%. The air mass flow is 1.3 lbs/sec..

A major part of the road testing was performed with the VW Microbus. (Fig. 37). The standard VW 1600 3-speed automatic transmission, without the torque converter, was used in this vehicle installation.

Fuel Economy: A driving schedule is given in Fig. 38 in accordance with an EPA proposal. It covers 100 miles and is composed partly of the FDC corresponding to city traffic, partly of steady average suburban traffic and partly of fast highway driving. For the 100 miles in this mixed traffic, the experimental gas turbine vehicle consumed 8.7 gallons of Diesel fuel compared with 5.3 gallons for the equivalent piston engine vehicle.

Analysis of these results shows that the higher fuel consumption of the gas turbine is mainly due to excessive idle consumption. The improvement of idling consumption (2 gal/hr vs. 0.5 gal/hr for piston engine) is one of the targets of future development. Also the fuel consumption at low steady speeds is still too high. At 30 miles per hour the experimental gas turbine fuel rate is 17 mpg compared to 27 mpg for the piston engine at comparable conditions. These shortcomings, compared to the piston engine car, can be improved by increasing the turbine inlet temperature (using recent progress in materials) and/or by incorporating: a power transfer, variable power turbine nozzles, power turbine by-passing (for idle) and taking the auxiliaries off of the gas generator shaft.

Exhaust Emissions: The FDC mass emissions of the VW-GT 70 compared with the U.S. automotive emission standards are shown in Fig. 39. It is shown that this experimental gas turbine car already meets the proposed standards up to 1976. With regard to the proposed standards for 1977, however; the

Inlet Conditions	60 °F, 29.5 inHg(15 °C, 1 bar)			
Power	75	HP	(55	kW)
Pressure Ratio	3.7			
Air Flow	1.3	lbs/s	(0.59	kg/s)
Gasifier Turbine Inlet Temp.	1674	°F	(912	°C)
Gasifier Speed	61 400	RPM	(1023	1/s)
Power Turbine Speed	50 600	RPM	(843	1/s)
Output Speed	4 550	RPM	(76	1/s)
Effectiveness of Regenerator	0.8			

Fig. 36 Engine Full-Power Specification for VW-GT 70

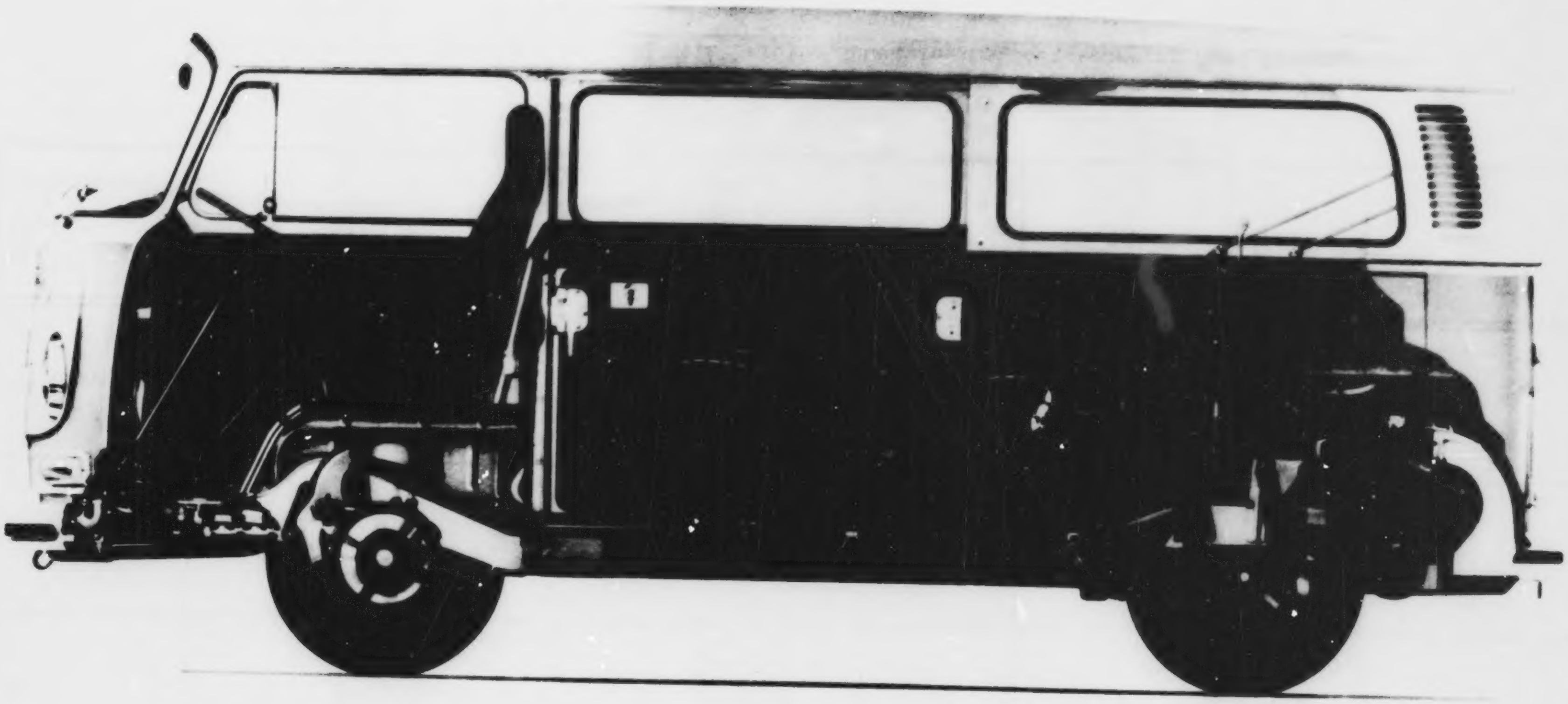


Fig. 37 Test Vehicle VW Microbus with Gas Turbine VW-GT 70

					VW - GT 70		PISTON ENGINE	
mode	% time	mean speed mph	minutes	miles	kg	gallons Diesel	kg	gallons Gasoline
FDC	50	19.84	100	32.8	13.9	4.49	6.5	2.35
Suburban	33	30	66	32.6	5.9	1.91	3.0	1.11
Highway	17	60	34	33.6	7.1	2.31	5.0	1.83
Total			200	100	26.9	8.71	14.5	5.29

Fig. 38 Typical Passenger Car 100-Mile Driving Schedule and Corresponding Fuel Consumption

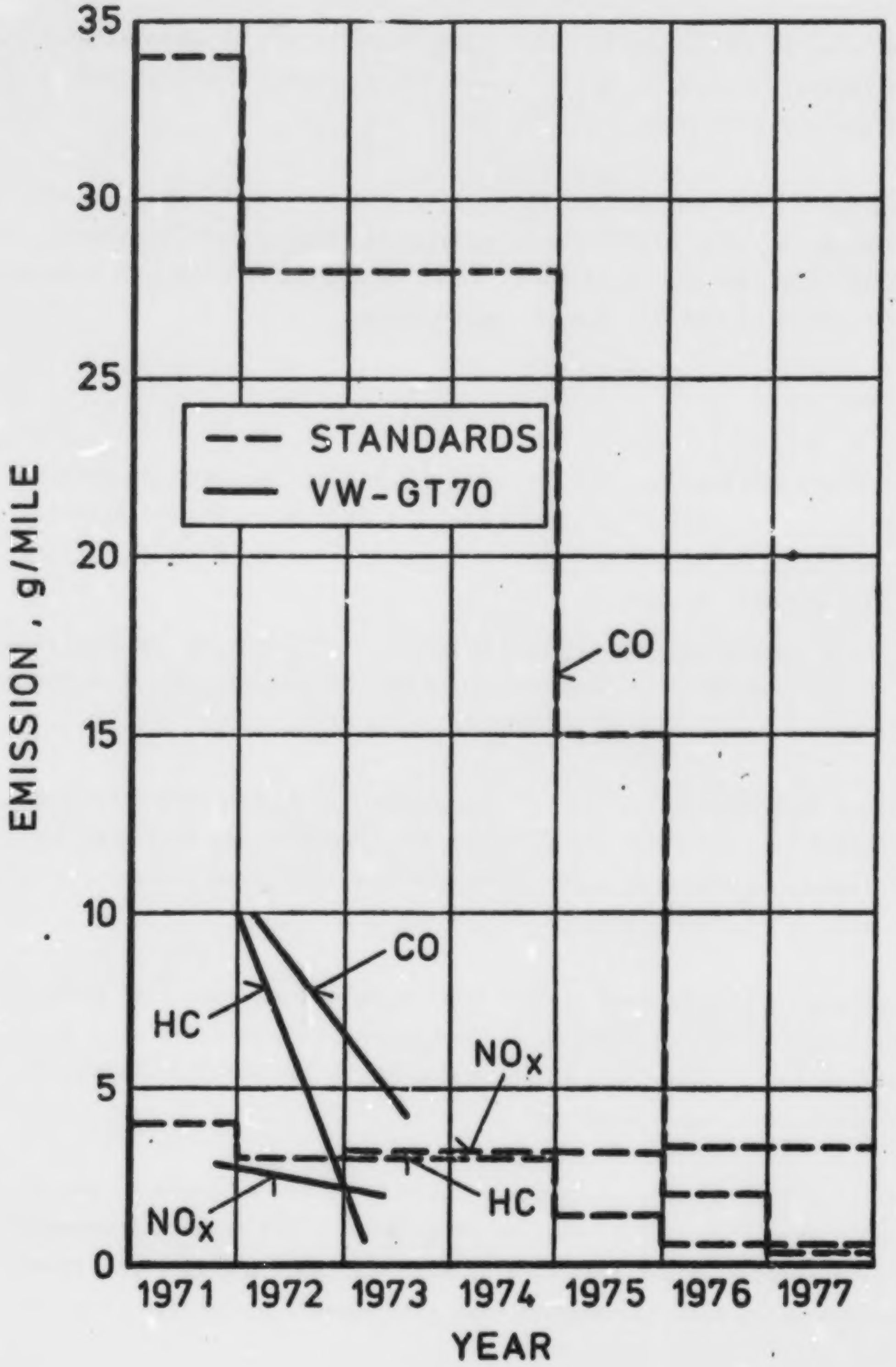


Fig. 39 US Federal Automotive Emission Standards and Gas Turbine Test Vehicle Emission

NO_x emission is still much too high. Improvements can be achieved with better fuel-air premixing, better combustion temperature control and burned gas recirculation.

Conclusions: From the results of tests on this very small first generation gas turbine, it is concluded that although this engine shows no significant advantages over the piston engine in vehicle road performance, it does show big advantages in low emission characteristics.

Questions: None

C. Chrysler Baseline Gas Turbine Program - Review and Status by George J. Huebner, Jr., Director of Research, Charles Wagner, Project Manager, and Tom Golec, Supervisor, Gas Turbine Development, Chrysler Corporation, Detroit, Michigan

Background, Current Status and Projections: The history of the gas turbine at Chrysler dates back to some initial design studies in 1939, with the first gas turbine powered automobile being built in 1953.

Beginning in 1963, fifty vehicles equipped with a fourth generation engine were tested by a sampling of 203 consumers. Response was very positive, problem areas were defined, and plans went ahead for a more extensive evaluation with an improved fifth generation engine.

This program was redirected in 1966 when it became apparent that oxides of nitrogen were a serious problem. Efforts since then have resulted in a sixth generation powerplant, which is serving as the Baseline Engine for the current development program.

Gas turbine fuel economy/performance characteristics at present compare favorably with typical I.C engines (Fig. 40). Short range improvements through augmentation are indicated by Fig. 41. With a 3 to 4 year development, adaptation to a sub-compact size also appears attractive (Fig. 42).

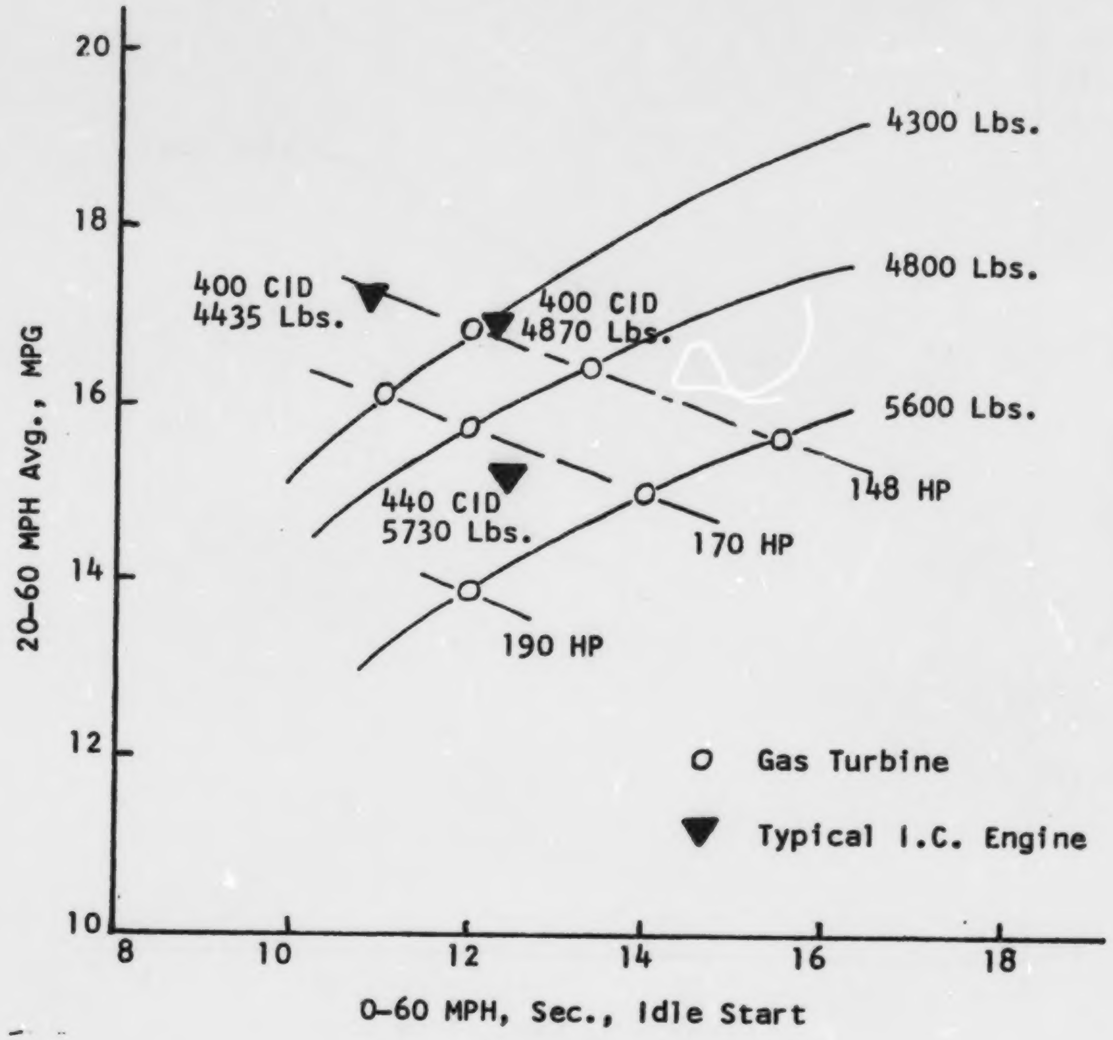


Fig. 40 Gas Turbine Performance

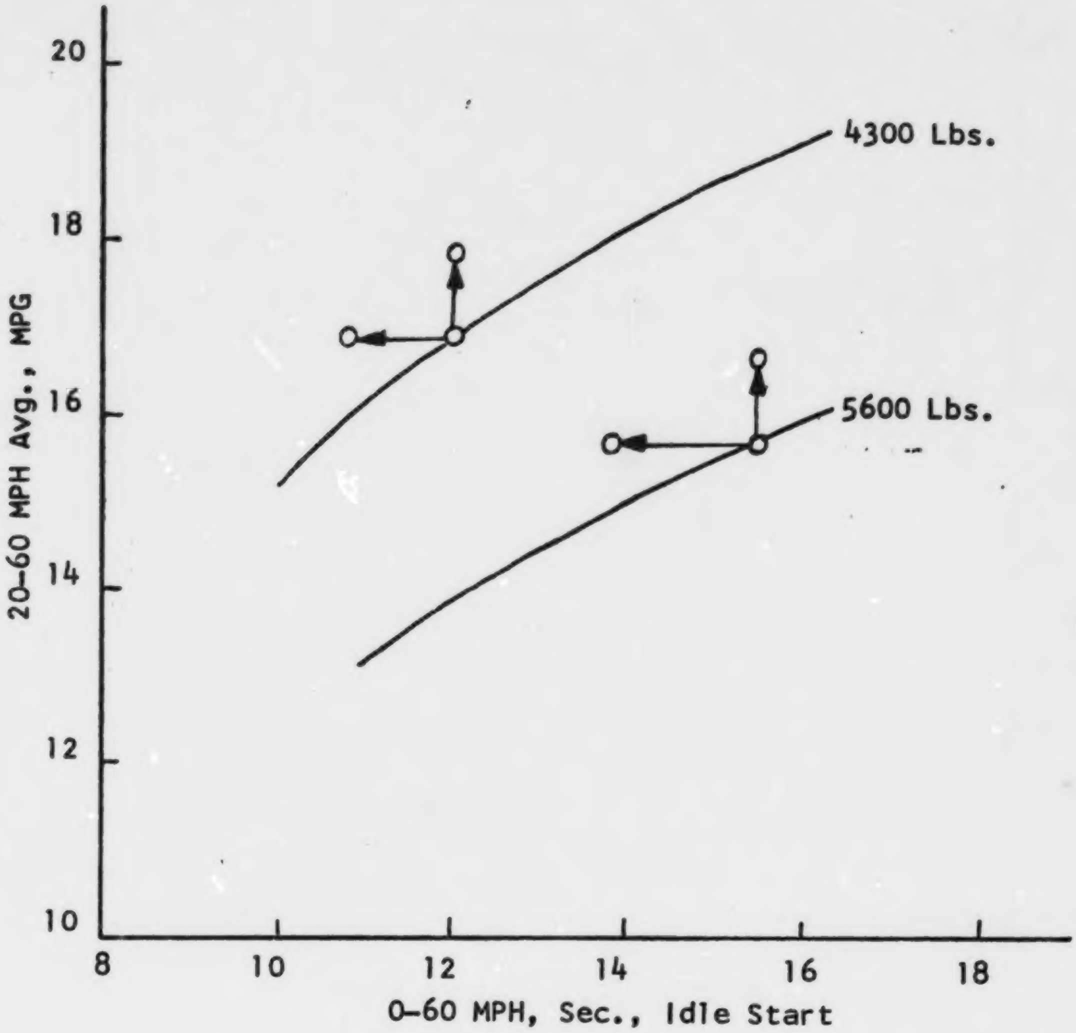


Fig. 41 Effect of Peak Power Augmentation on Base Engine Performance

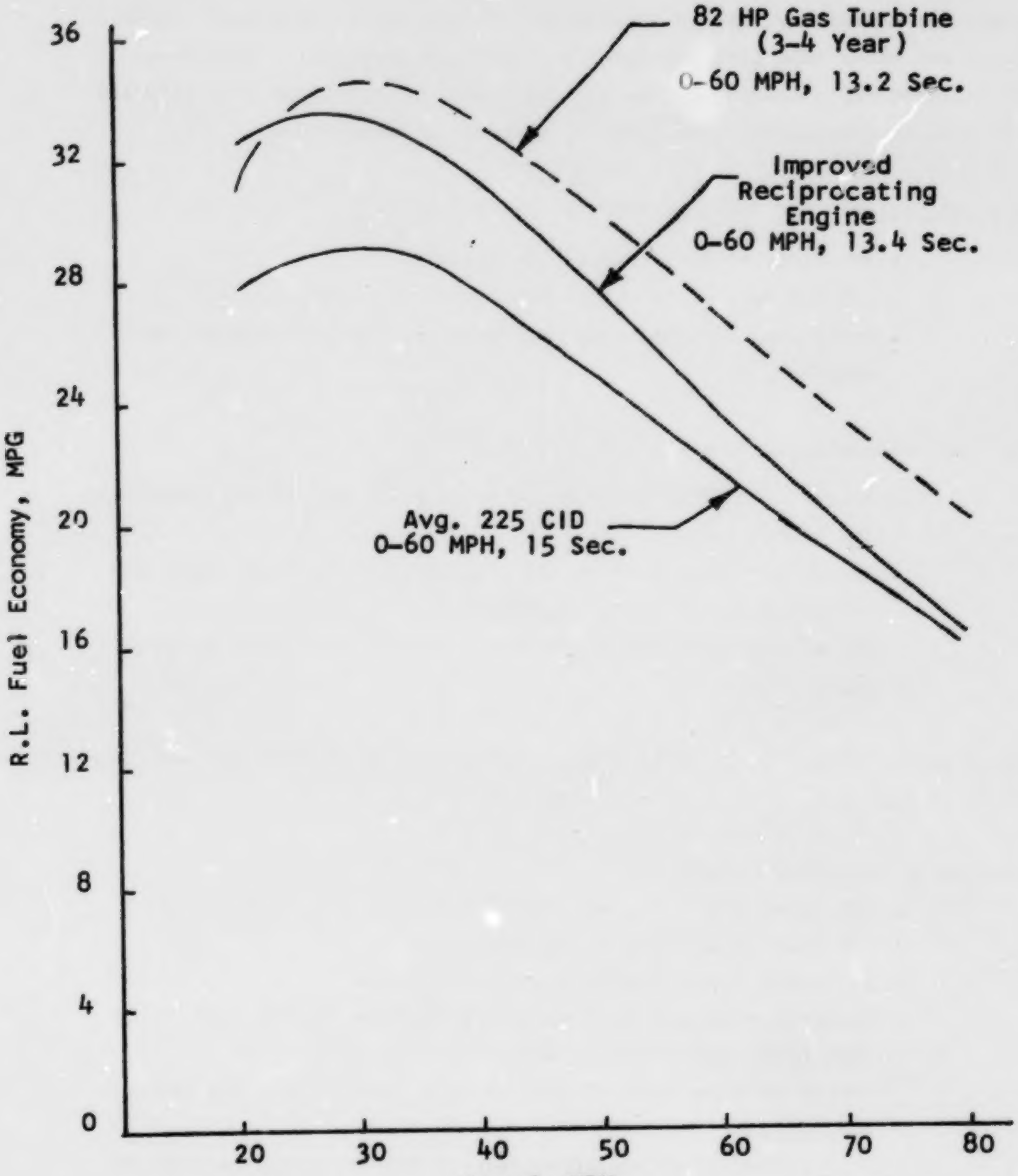


Fig. 42 Sub-Compact Fuel Economy

Potential engine improvements currently under consideration include higher component efficiency, higher temperature operation, variable inlet guide vanes and water injection for power augmentation (Fig. 43). Additional significant improvements will be realized when the development of ceramics and ceramic composites allow a major increase in temperature.

Program Status: The Baseline contract calls for:

- Building Baseline engines and vehicles.
- Conducting and coordinating improvement programs.
- Designing, building, and demonstrating upgraded engines and vehicles.

The improvement objectives are:

- Achieve the original 1976 .41 HC, 3.4 CO, and .4 NO_x grams/mile emissions levels.
- Demonstrate fuel economy significantly better than comparable reciprocating SI engine vehicles.
- Demonstrate that the engine has potential for low cost mass production.

The Baseline Engine is Chrysler's sixth generation automotive gas turbine, Figs. 44 and 45.

Program achievements to date are:

- Delivered 5 of 7 engines (2 for test cell use, 1 for NASA, 1 for endurance, 1 for a vehicle).
- Delivered 1 of 3 vehicles.
- Extended endurance testing on the Baseline Engine from 3000 to 3500 hours (discussed in more detail below).
- Completed free-rotor (Figure 46) acceleration and fuel economy evaluations.
  - A typical acceleration test visicorder trace is shown in Figure 47, with a summary of the results shown in Figure 48.

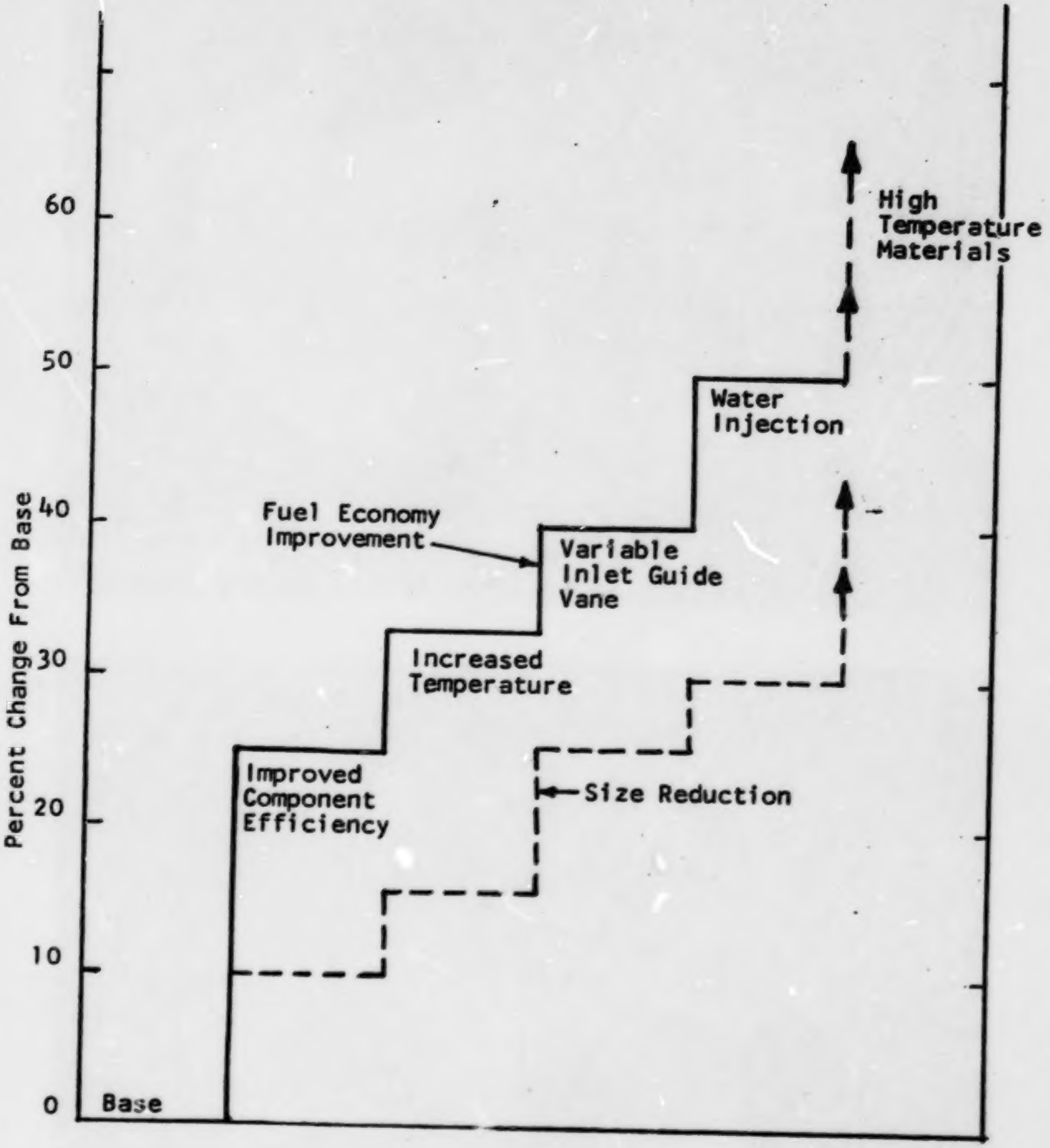


Fig. 43 Projected Gains for Automotive Gas Turbine

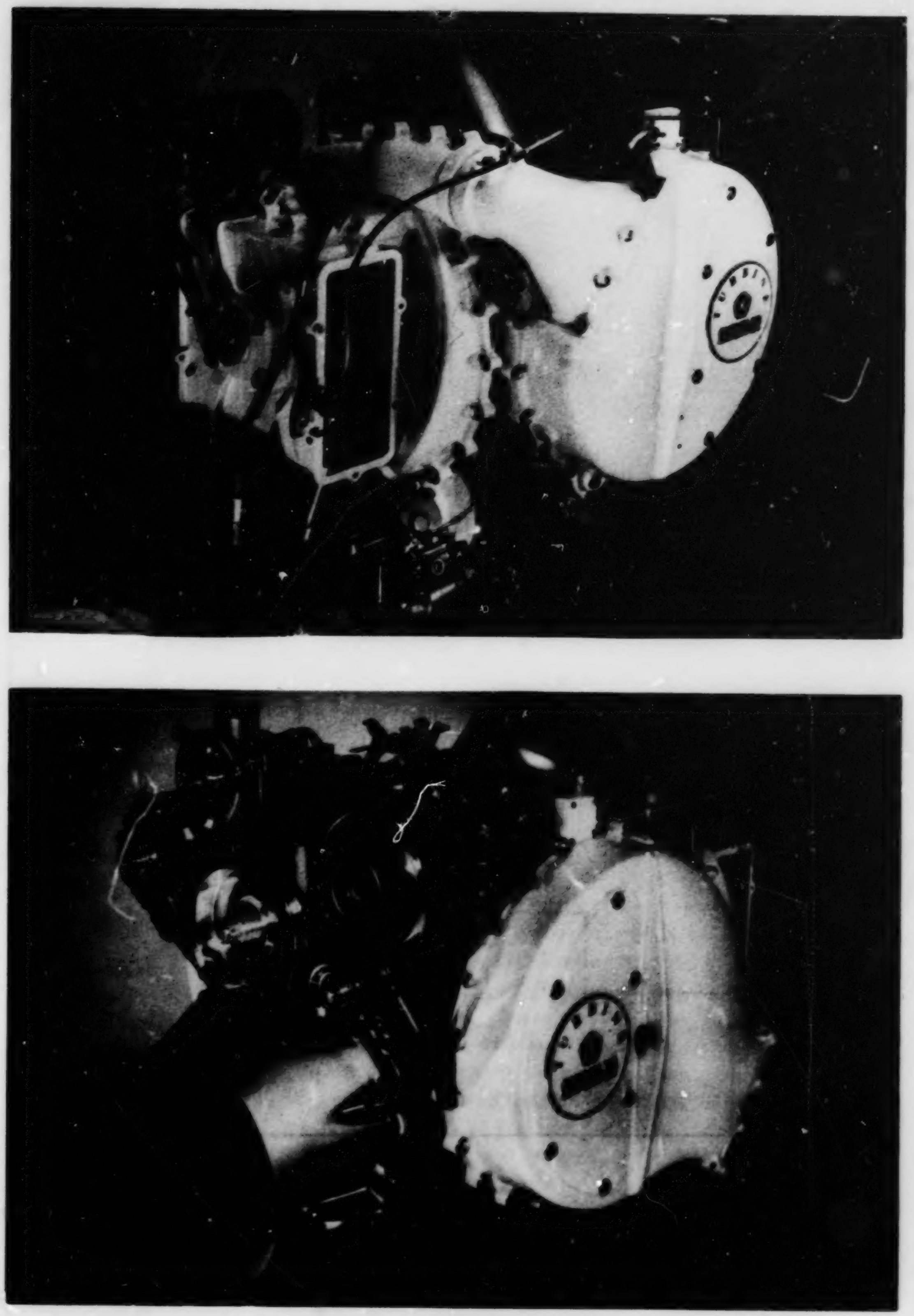


Fig. 44 Baseline Engine

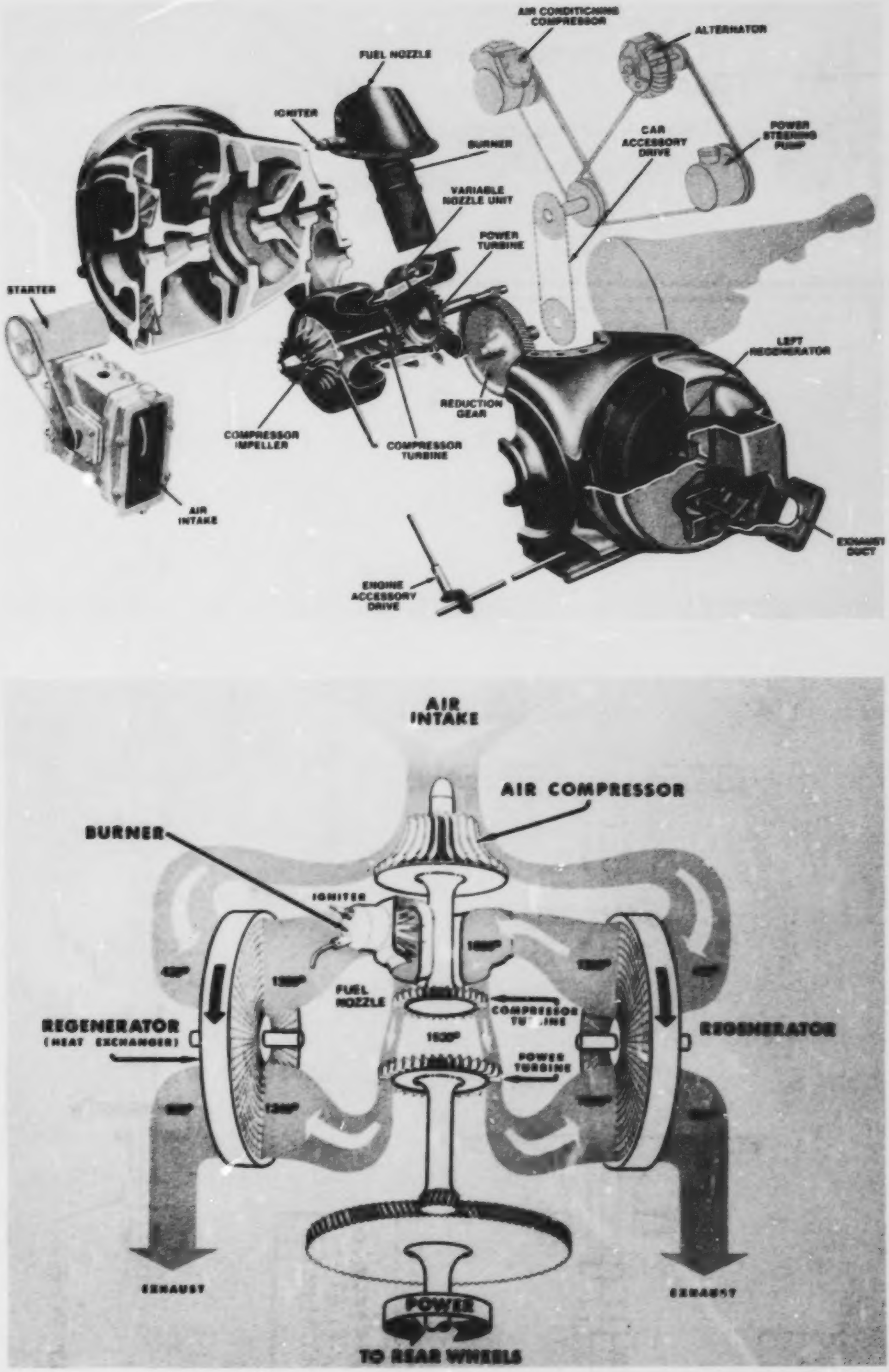

AIR CONDITIONING COMPRESSOR
ALTERNATOR
FUEL NOZZLE
IGNITER
BURNER
CAR ACCESSORY DRIVE
POWER STEERING PUMP
VARIABLE NOZZLE UNIT
POWER TURBINE
STARTER
LEFT REGENERATOR
REDUCTION GEAR
COMPRESSOR IMPELLER
COMPRESSOR TURBINE
AIR INTAKE
EXHAUST DUCT
ENGINE ACCESSORY DRIVE
AIR INTAKE
AIR COMPRESSOR
BURNER
IGNITER
FUEL NOZZLE
COMPRESSOR TURBINE
REGENERATOR (HEAT EXCHANGER)
REGENERATOR
POWER TURBINE
EXHAUST
EXHAUST
POWER
TO REAR WHEELS

Fig. 45 Chrysler Corporation Sixth Generation Gas Turbine Engine

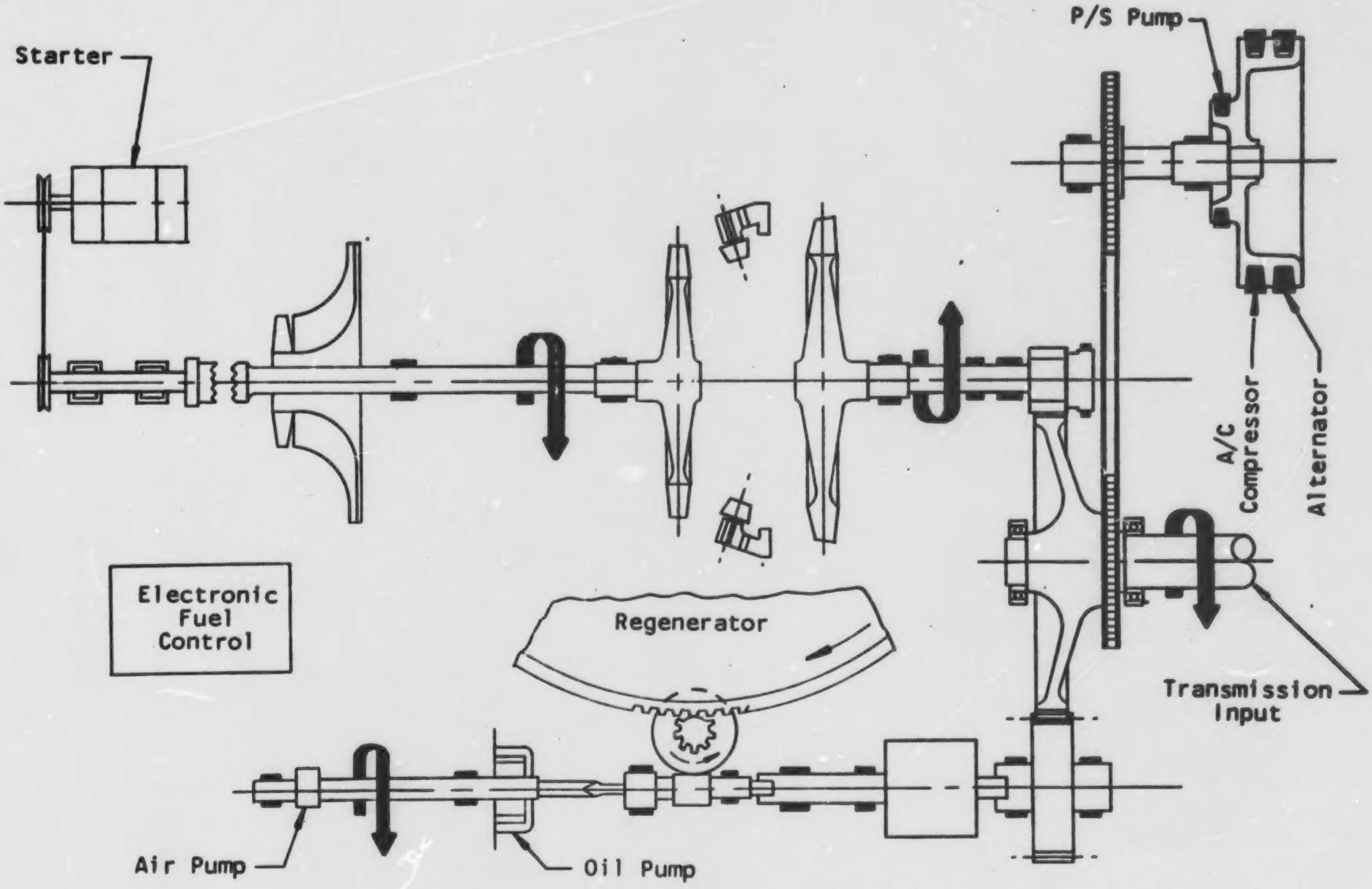

Starter
P/S Pump
A/C Compressor
Alternator
Transmission Input
Electronic Fuel Control
Regenerator
Air Pump
Oil Pump

Fig. 46 Baseline Engine Free-Rotor Concept

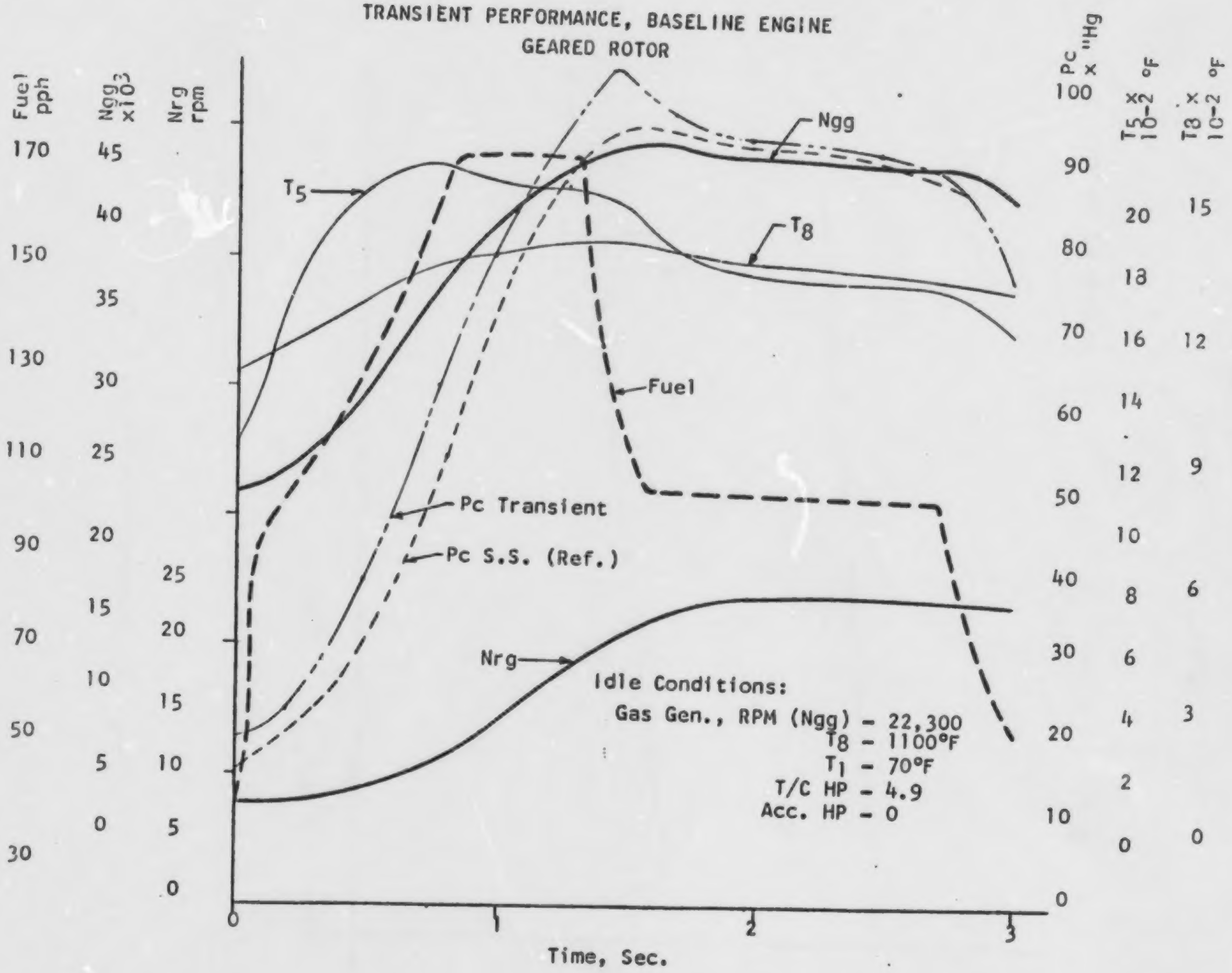


Fig. 47 Transient Performance — Baseline Engine Geared Rotor

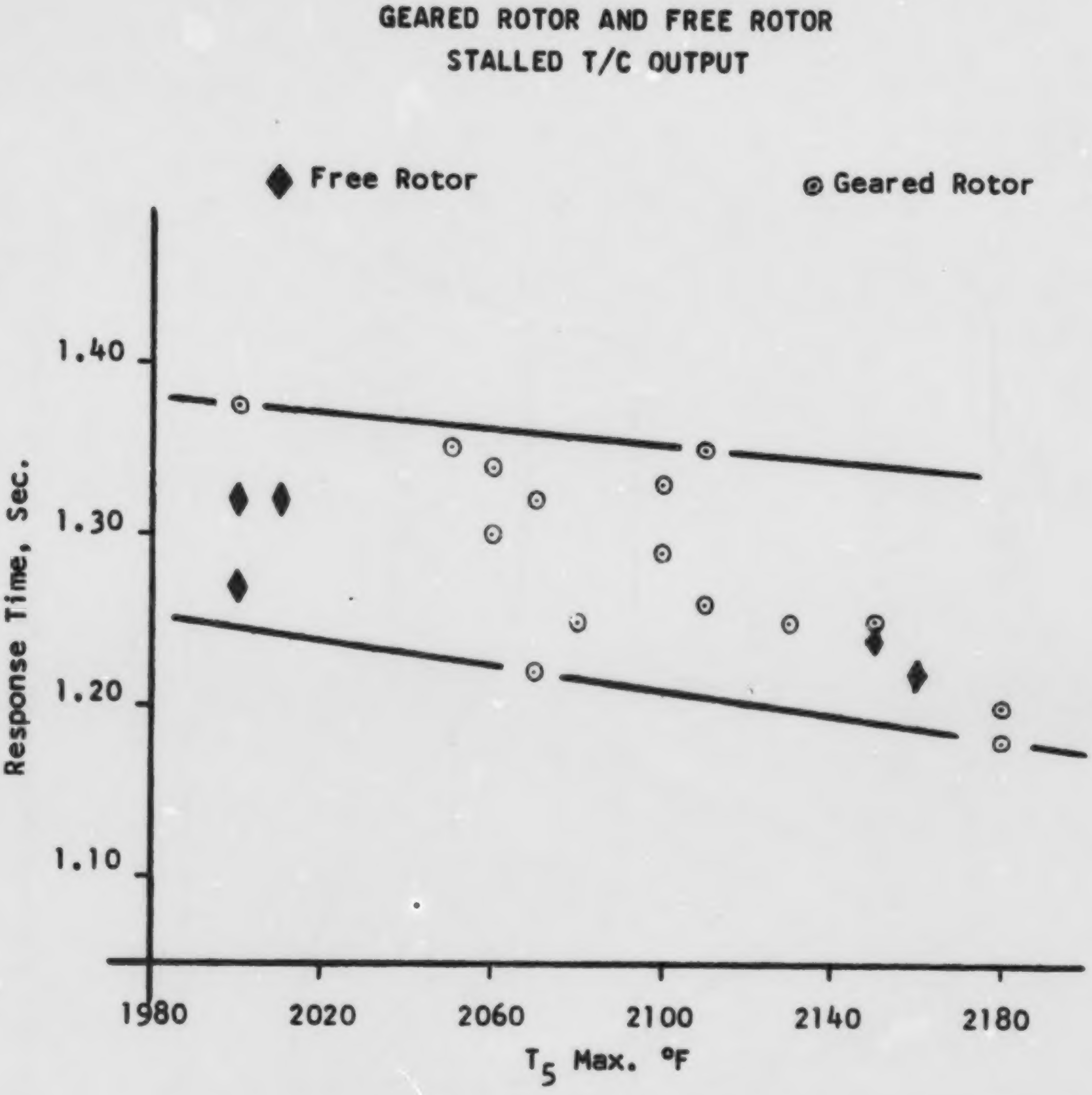


Fig. 48 Response Time Versus T_5 Max.

Of interest is the high transient compressor collector pressure (Fig. 49).

- Low speed fuel economy comparison is shown in Fig. 50. Inferred is a negligible difference between the free and the geared rotor over a typical driving cycle.
- To assist in design of a free-rotor regenerator drive, core-speed/fuel-flow tests (Fig. 51) were run.

Major efforts in process are work on:

- Adapting ceramic regenerators to the engine to allow increased cycle temperature. An Elastomeric drive (Fig. 52) will be used with a mechanical attachment as back-up.
- Evaluating variable inlet guide vanes (Fig. 53) for power augmentation and reducing low speed fuel consumption.
- Development of an integrated control system, discussed in Section III-F.
- Evaluation of potentials for vehicle fuel economy improvements with a torque converter lock-up.
- Continuing support to NASA's engine and aerodynamic component programs (See Section III-D).
- Initial free rotor and Upgraded Engine design studies. A direct power turbine to engine accessory drive appears to be the best approach. Oil and atomizing air would be available at starting through a starter-connected over-running clutch. The Upgraded Engine design plan is summarized in Fig. 54.

Major efforts soon to commence are:

- Selecting and procuring turbine parts and materials for increased cycle temperature running.
- Evaluation of power augmentation by water injection.
- Evaluation of Solar's and Chrysler's proprietary combustor work directed toward achieving program emissions goals. (See Section III-E).

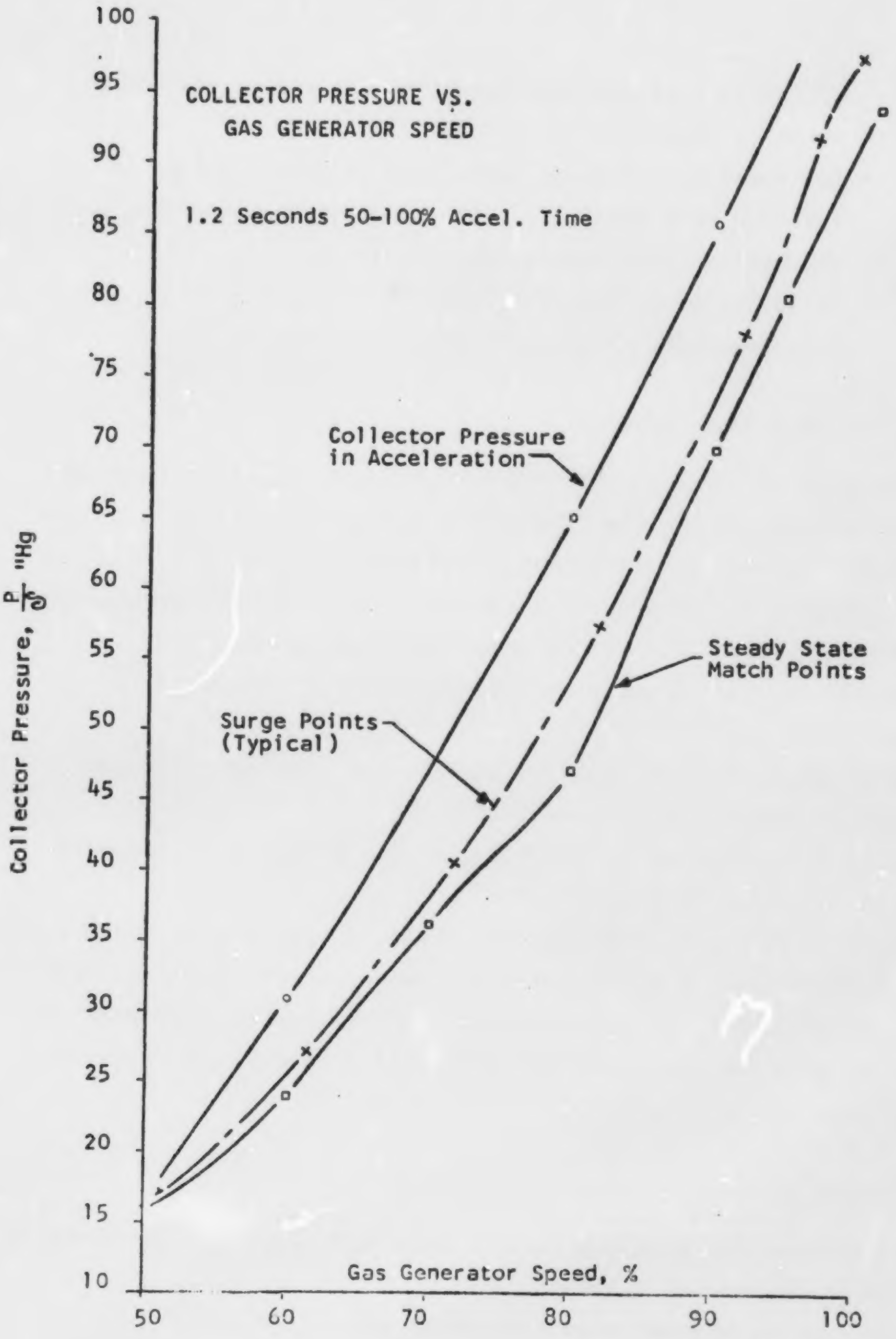


Fig. 49 Collector Pressure Versus Gas Generator Speed

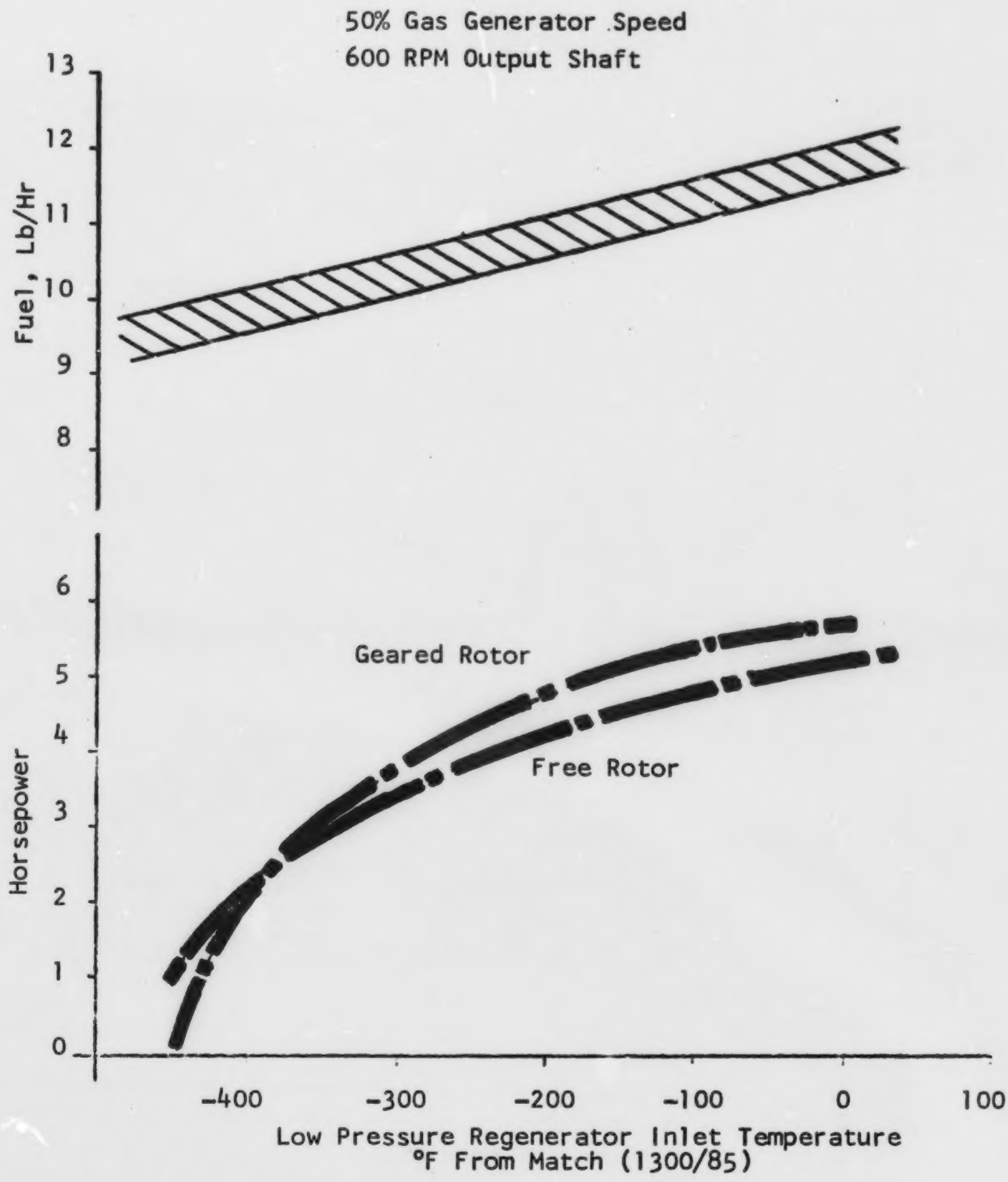


Fig. 50 Curb Idle Fuel Consumption – Free Versus Geared Rotor

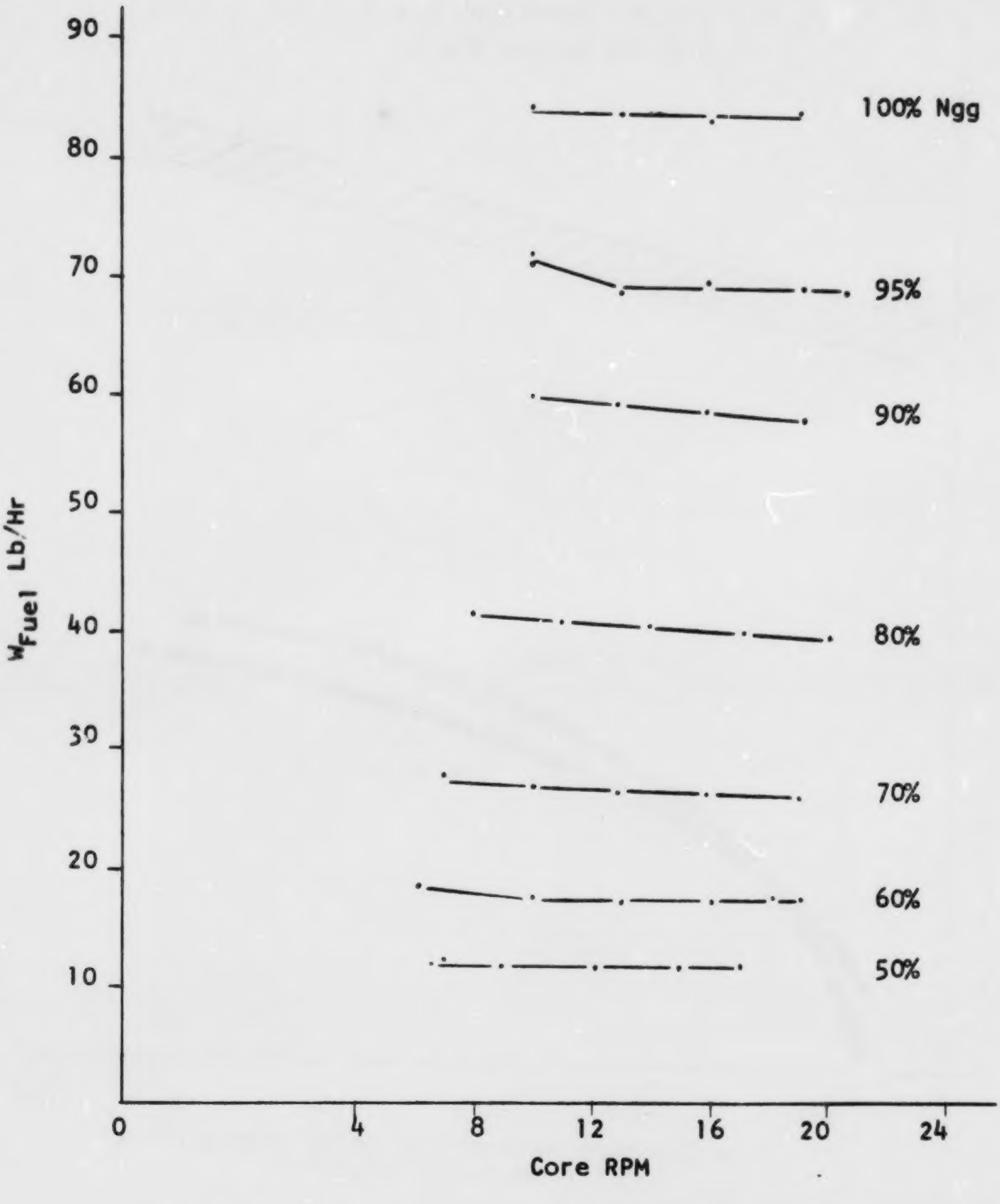


Fig. 51 Free Rotor Tests — Fuel Flow Versus Core Speed

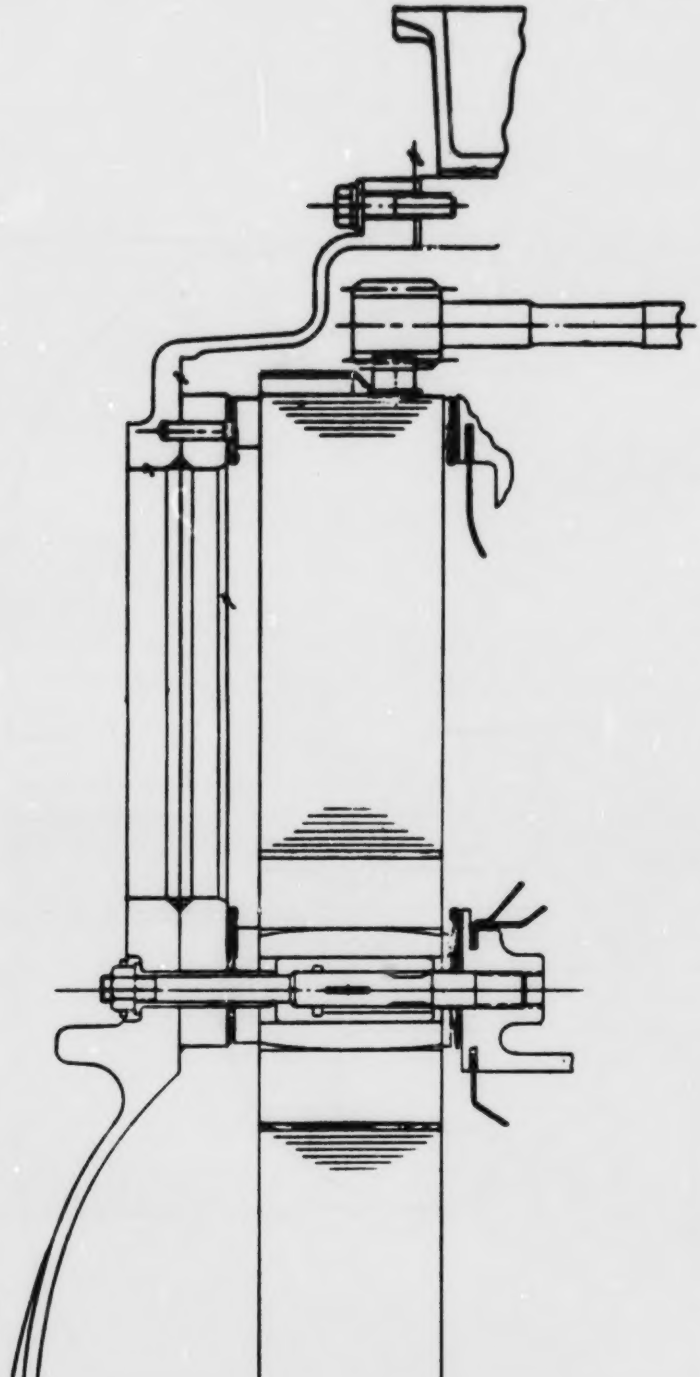


Fig. 52 Ceramic Regenerator Drive - Elastomer Ring-Gear Mount

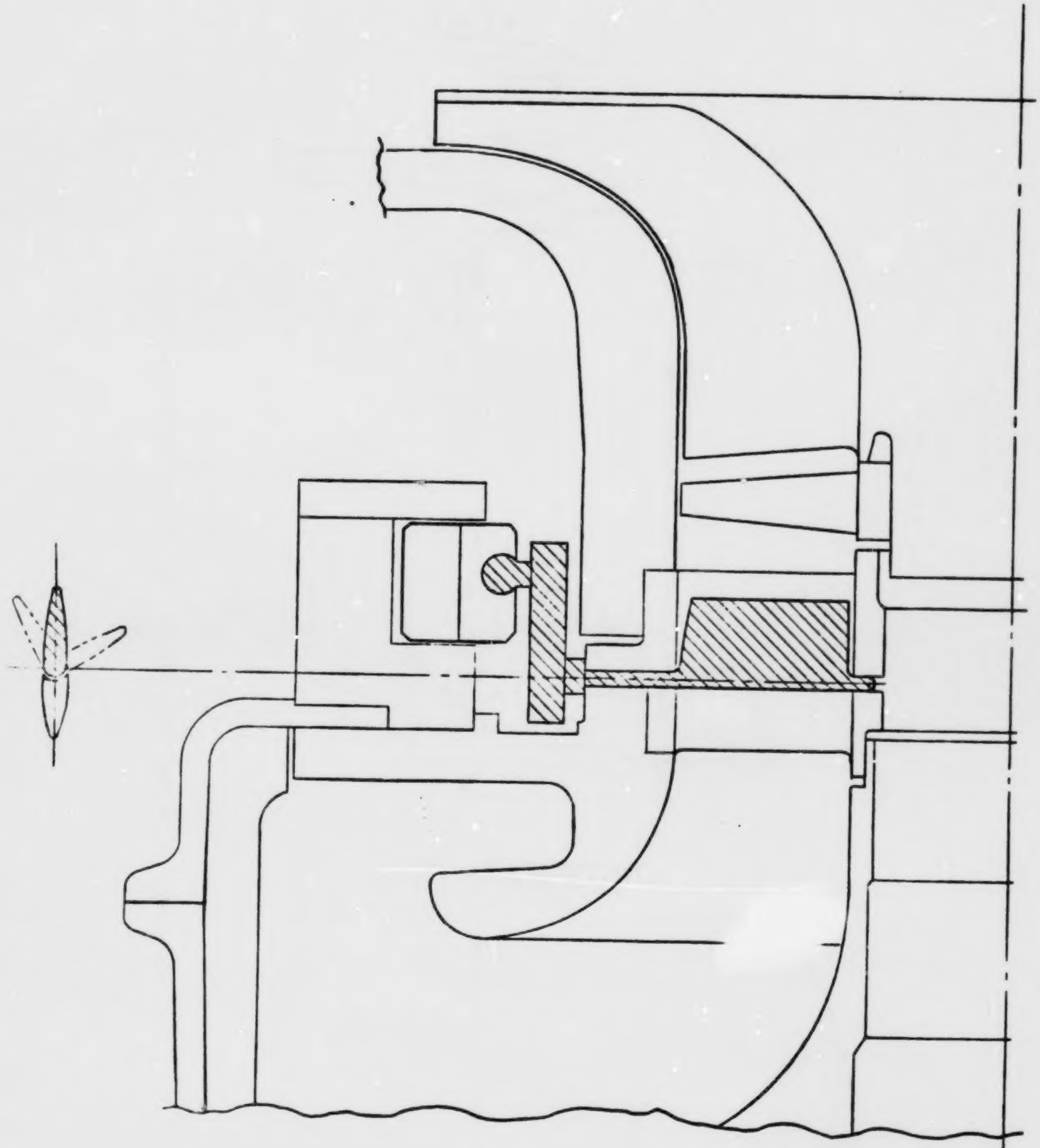


Fig. 53 Variable Inlet Guide Vanes

- Schedule Considerations
  - Design Must Proceed Parallel With Improvement Efforts
  - Set Reasonable Goals
  - Assume Goals Will Be Met
- Design

• Airflow .70 x Baseline Regenerator 1.00 x Baseline . Low Speed Fuel Economy	105 HP
• Increase T.I.T. 75°F	117 HP
• Increase Component Efficiencies	125 HP
• Increase Pressure Ratio With V.I.G.V. At Constant T.I.T.	137 HP
• Utilizing Cooler Ambients With Hot Ambient Water Injection, Or Overspeeding, Or Further Increases In T.I.T.	150 HP

Fig. 54 Upgraded Engine Design Plan

- Evaluation of a turbine wheel made by Pratt-Whitney "Gatorizing" process. (See Section III-G).

The plan for the three Baseline Vehicles to be used in this program are outlined in Fig. 55. A photograph of the first vehicle installation is shown in Fig. 56.

Endurance Program: The Baseline contract endurance goal is 3500 hours. To achieve this goal on the Baseline Engine, a powerplant which had accumulated 2869 endurance hours prior to the contract (1968-1969) was reactivated for continued testing. During September, 1973, it achieved the 3500-hour milestone. A second 3500-hour endurance test will be initiated later in the program for upgraded component evaluation.

An accumulated background of specific endurance tests (Fig. 57) led to the conclusion that for an effective accelerated life test, steady state running was virtually meaningless. A test cycle should include several starts, part and full throttle accelerations, and a shutdown period to expose rotor bearings to soak back temperatures.

The present test cycle (Figs. 58 and 59) was based on such concepts. In the order of priority, thermal considerations (testing of burner and turbine elements) were given precedence over mechanical considerations (impeller low cycle fatigue, etc.). Average equivalent vehicle speed is 49 mph.

An automatic programmer controls the engine over the one-hour cycle. Safeties are provided for overtemperature, overspeed, low oil pressure, no start condition, etc.. Strip chart recorders provide a continuous record of events.

A detailed inspection after 3222 endurance cycles (Figs. 60 and 61) substantiates the claim that an automotive gas turbine has excellent life potential. This test was the equivalent of a vehicle driving the cycle for 160,000 miles. Except for some component updating and life test development (regenerator ring gears and linerless insulation), a part was not replaced until

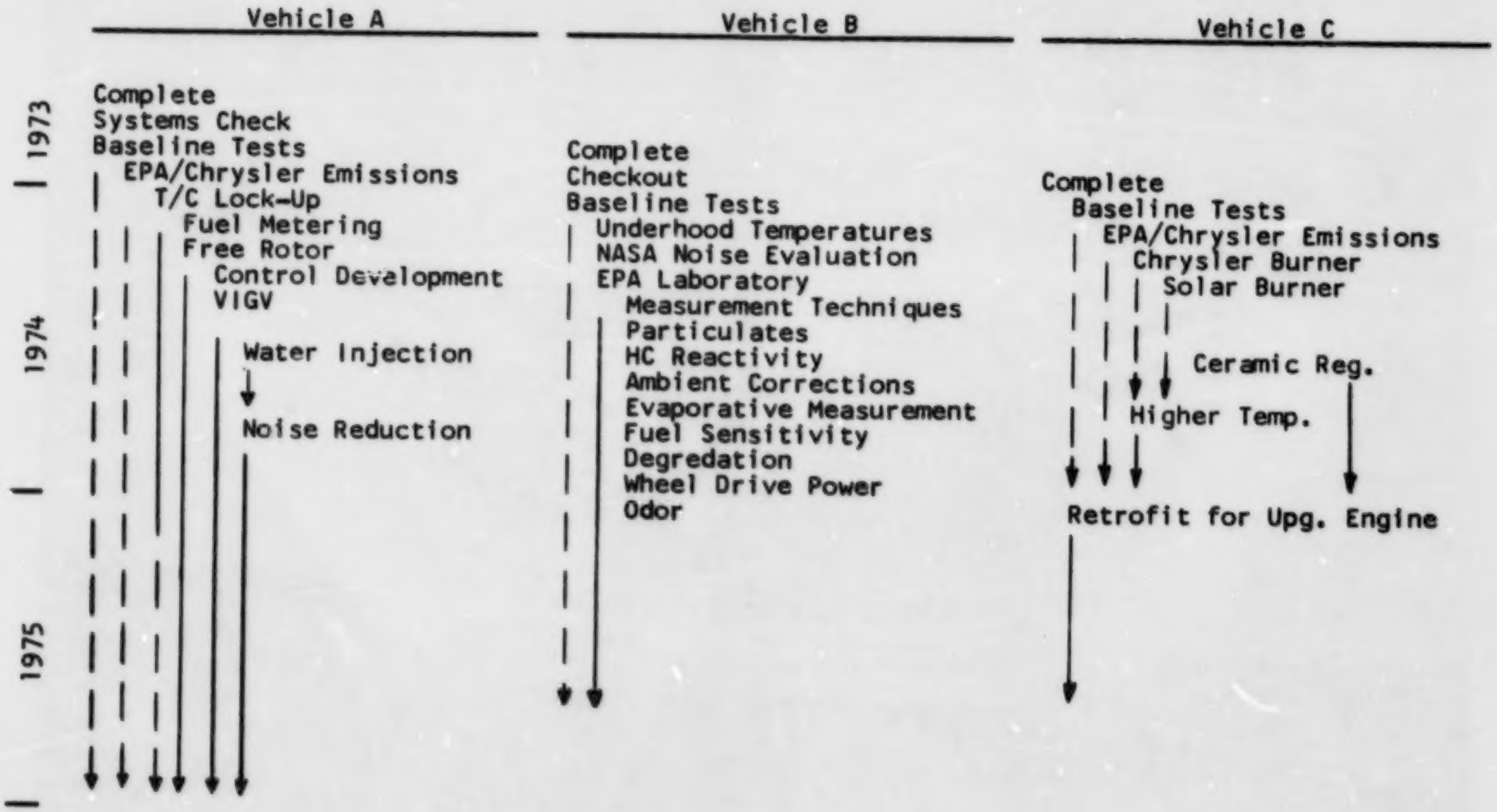

Vehicle A
Vehicle B
Vehicle C
1973
1974
1975
Complete
Systems Check
Baseline Tests
EPA/Chrysler Emissions
T/C Lock-Up
Fuel Metering
Free Rotor
Control Development
VIGV
Water Injection
Noise Reduction
Complete
Checkout
Baseline Tests
Underhood Temperatures
NASA Noise Evaluation
EPA Laboratory
Measurement Techniques
Particulates
HC Reactivity
Ambient Corrections
Evaporative Measurement
Fuel Sensitivity
Degredation
Wheel Drive Power
Odor
Complete
Baseline Tests
EPA/Chrysler Emissions
Chrysler Burner
Solar Burner
Ceramic Reg.
Higher Temp.
Retrofit for Upg. Engine

Fig. 55 Baseline Vehicle Program

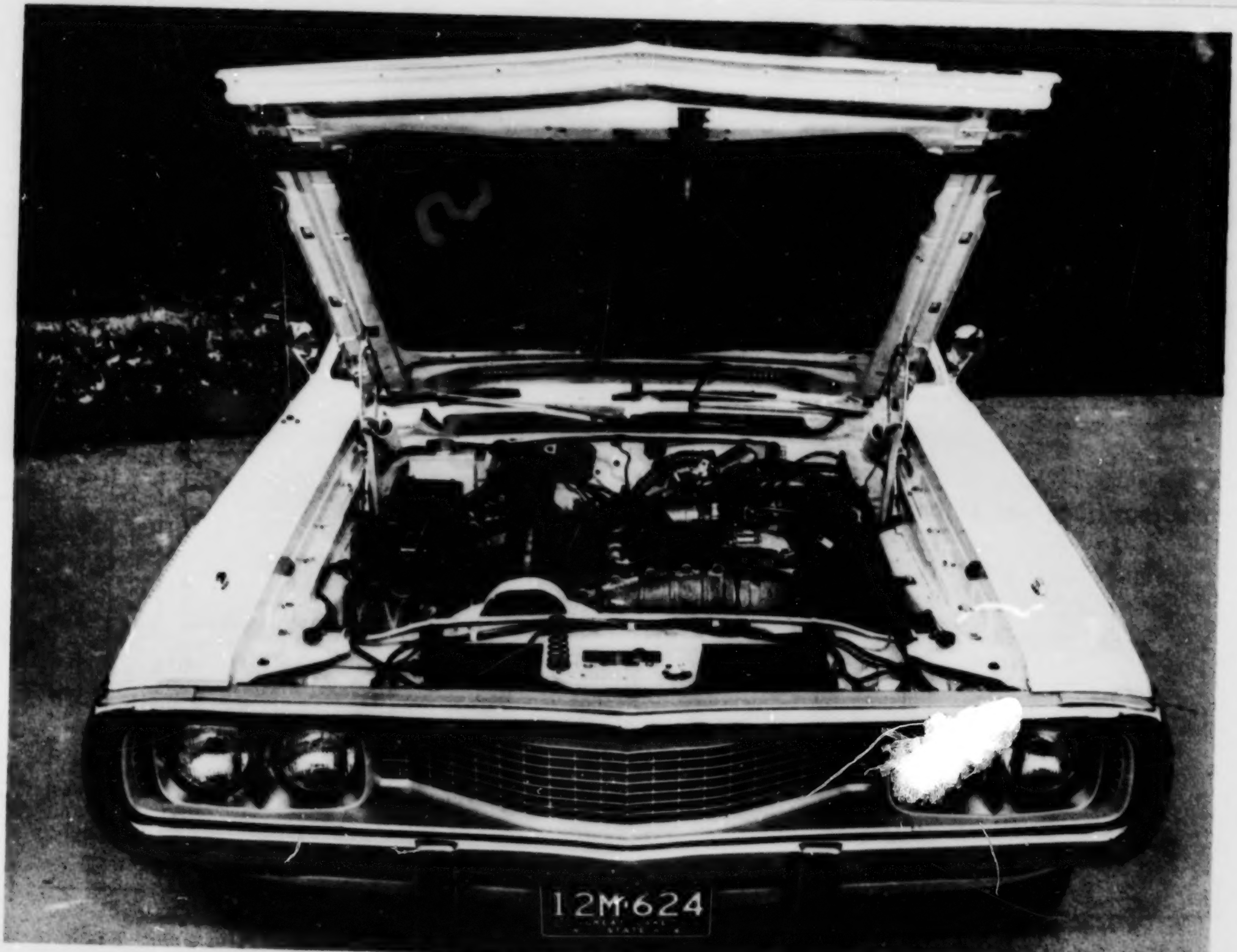


Fig. 56 Gas Turbine Baseline Vehicle

EARLY EXPERIENCE

- Initial endurance test cycle, circa 1963
  Purpose - Establish datum

- W.O.T. tests, 1850°F turbine inlet temperature and 44,610 rpm rotor speed.

  Purpose - Evaluate creep, oxidation, sulfidation of CTW, CTN, burner, etc.

- Regenerator core matrix thermal cycle endurance

  Purpose - Expose core matrix and seals to maximum temperature cycling.

- Starting endurance

  Purpose - Low cycle fatigue, CTW, bearing, regenerator core matrix.

- General vehicle endurance, drive train endurance, Proving Grounds, 50 car program, car 017 prototype 1963-4 100,000 miles.

- Rotor bearings soak back tests
  Study bearing coking problem

Fig. 57 Background of Endurance Testing

GAS TURBINE ENDURANCE RECORD
PP-102-24 AV
Typical Speed Recordings Shown

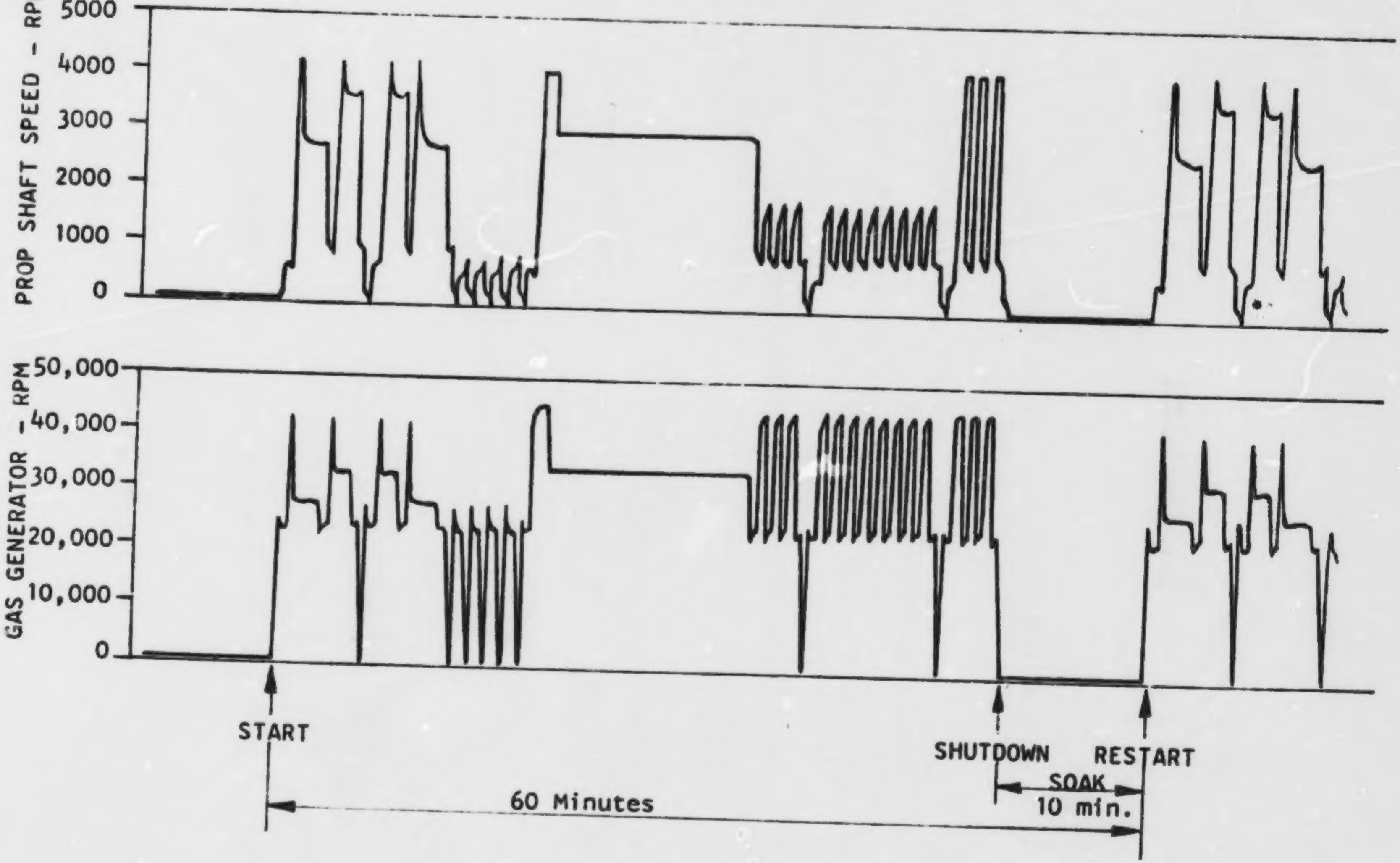


Figure 58

Vital Statistics -

- Duration - 60 Min.
- Total shut down time 14.5 min., includes 10.5 min. soak period.
- Average vehicle speed (assume typical axle ratio, tire size, etc.) - 49 MPH
- Starts/Cycle - 9.
- Total rotor accelerations/cycle 19, WOT accelerations 15.
- Approximate 16 hour/day - 1 Cold start/day
- Fuel - Diesel 1.
- Lubricant MS 4228 - 180/230 °F Temperature.
- Operating ambient temperature 70 - 90°F.

Fig. 59 Description of Accelerated Endurance Test — Summary of 1-Hour Endurance Cycle

P.P. No.6 Build 102-24 B.W.   Room No. 125   Date 10/1/73
Total Hours 3620.0

	S/N				
Engine Housing Assy.	102	***			3620.0
Insulation Type CR95A		***			3620.0
Dump Valve	9	***			3620.0
Power Turbine Nozzle Support	116	***			3620.0
Ring Gear	129	***			3620.0
Outer Shroud	114	***			3620.0
Inner Shroud	116	***			3620.0
Seal Ring Support	105	***			3620.0
Oil Sump Housing Assy.	12	***			4022.6
Oil Sump Worm Gear Housing	8	**	(1)		1724.7
Oil Sump Worm	6A	***			3620.0
Worm Wheel	8A	***			3620.0
Pinion Shaft - Left	408	*	(2) 12P	"Des.3"	110.3
Pinion Shaft - Right	405	*	(3) 12P	"Des.3"	585.6
(1) Oil Sump Worm Gear Hsg.	12	**			2298.0
(2) Pinion Shaft Left	12A	**	16P		686.5
Pinion Shaft Left	14	**	16P		2347.9
Pinion Shaft Left	405	*	12P	"Des.3"	475.3
(3) Pinion Shaft Right	11	**	16P		198.1
Pinion Shaft Right	13	*	12P	"Des.1"	488.4
Pinion Shaft Right	14	*	12P	"Des.2"	701.2
Pinion Shaft Right	13	**	16P		1646.7
Gas Generator Bearing Carrier	108	***			4557.9
Cover (Mach. for Insert) } Insert	110	**			2128.4
Burner Vortex	105	***			3940.0
Turbine Wheel	2038	***	(4)		2925.3
Nozzle	2025	***	(5)		3232.2
Diffuser Plate	130	**	(6)		1724.7
Cascade	179	**	(7)		655.2
Worm	134	**			3099.0
Worm Wheel	23	***			4223.3
Impeller Rotor Assy 851 Long Shroud	138	***	(8)		3620.0
Compressor Inducer		***			3620.0
Compressor Impeller		***			3620.0
Bevel Gear Set	19	***			3620.0
Oil Pump Assy.	127	***			3620.0
Air Pump Assy.	114	***			3620.0
(4) Turbine Wheel 713C MDC Coated	2029	**			306.9
713C Arcuate Slots	2038				See Above
713C Cast Rim, Stress Risers, Arcuate Slots	2043	**			398.1
(5) Nozzle 713C LC MDC-1 Coated Ellip. Fillets	2025				See Above
180 Heavy Flange Ellip. Fillets	2038	**			398.1
(6) Diffuser Plate	111	**			2445.7
(7) Cascade	180	*			1590.5
(8) Impeller Rotor Assy. 2-Shroud Replacements	138				See Above

	S/N			
Power Turbine Hsg. Assy.	112	**	(9)	2881.7
Reduction Gear Set	2	**		3312.5
Power Turbine Rotor	2016	**	(10)	866.8
Anti-Thrust Washer		**		2670.0
Thrust Washer	40	**		2670.0
Reduction Gear Hsg. - Frt.				
Reduction Gear Hsg. - Rear				
Reduction Gear Seal				
(9) Power Turbine Assy	106	**		682.7
Power Turbine Assy	109	**		305.9
(10) Power Turbine Rotor	2002	***		3831.0

Regenerator Assemblies	Left				Right			
Core Assy.	351	**	(11)	1364.0	348	**		2442.9
Inner Crossarm	4-107	**	(11a)(12)	585.6	4-106	**	(13)	585.6
Inner Front Rim	20-2	**	(11a)(12)	563.3	20-26	**	(13)	563.3
Inner Rear Rim	120-28	**	(11a)(12)	563.3	120-33	**	(13)	563.3
Inner Base Plate Assy	403	**		563.3	402			
Outer Base Plate Assy	403	**		563.3	402			563.3
Outer Crossarm	A-38	**	(11a)	1341.7	B-40	**		2420.6
Outer Rear Rim	19-28	**	(11a)	1341.7	19-14	**		2420.6
(Outer Seal "D"								
Cover Assembly	L-108	***		3620.0	R-108	***		3620.0
Regenerator Ring Gear								

(11)	Core Assy Left	336		** 2068.0
(11a)	Inner Crossarm	719H		** 1893.6
	Inner Front Rim	19-23		** 2002.3
	Inner Rear Rim	120-20		** 2002.3
	Outer Crossarm	19-A		** 2689.9
	Outer Rim	19-2		** 2672.0
(12)	Inner Crossarm	761H	} Run with Core 351	** 778.4
	Inner Front Rim	20-25		** 778.4
	Inner Rear Rim	19-28		** 778.4
(13)	Inner Crossarm	866H	} Run with Core 348	** 1804.5
	Inner Front Rim	20-22		** 1804.5
	Inner Rear Rim	120-29		** 1804.5

Burner Cover Assy *	403	**	(14)	270.8
Insulation Type				
Burner Tube Assy	407	*	(15)	276.4
Fuel Nozzle	403	**	(16)	260.6
Igniter	401	*	(17)	338.0
Mixer	402	*		254.0
Ignition Unit				
Swirlplate			(18)	
Engine Auxiliaries (Misc.)				
Fuel Control	406	*	(19)	240.5
Nozzle Actuator	30	***		3620.0

Starter Motor	270-1	**		1419.7
Starter Clutch Assy.		***	No. Starts	30713
Starter Belt		***	No. Starts	12,006
Air Intake Assy	114	***		3620.0
Air Pump Relief Valve	100	***		3620.0
Vehicle Accessories				
Alternator	402	**		353.0
Power Steering Pump	403	*		353.0
A/C Compressor				
Transmission				
Torque Converter				
* Low Emission Burner				

(14) Burner Cover Assy	118**	Linerless Insul. Chrysler	1681.3
	114**		1893.2
(15) Burner Tube	112**		317.3
	116**		473.1
	119**		2256.0
	121**		447.4
(16) Fuel Nozzle	161**		1470.8
	152**		960.0
	175**		1271.0
(17) Igniter	N24**		711.9
	N30**		1001.8
	N31**		877.5
(18) Swirlplate	432-2**		1778.8
	511 **		1606.9
(19) Fuel Control	7 *		1441.4
	2 *		990.0
	4 *		583.9
	6 *		19.3
	12 *		131.2

*** Original Component
** Replaced by updated part, adequate life
* Problem Area

Fig. 60 A-128-1 Components Record – Endurance Power Plant

Complete Engine Component Log

Vital Statistics Totals

Accumulated Hours 3620

Endurance Hours 3222

Number of Cycles 3222

Miles - Estimated 160,000 (Endurance Hours Only)

Starts 30,713

Rotor Accels 61,218 @ WOT 48,330 (Endurance Hours Only)

Engine Depreciation 5 - 10%
(After Cleaning Compressor).

Fig. 61 Summary of Endurance Test Results Through October 1, 1973

it caused the engine to malfunction and/or caused a noise which would compel the average driver to take corrective action. Maintenance was limited to cleaning the compressor at specified time intervals and maintaining the oil level caused by minute leaks.

The compressor/inducer assembly at 3211 hours showed no evidence of erosion. However, the impeller was coated with a fine film of dirt which required maintenance at specified time intervals.

The 713C coated first stage nozzle at 2823 hours exhibited cracks in the leading edge at the fillet of the ID and OD on all blades, some chipping of the coating, and seven mid-radius cracks at the trailing edge. These deficiencies have not adversely affected the performance of the engine, and the part is continuing on test.

An updated turbine wheel at 398 hours showed no distress. This has arcuate slots machined at the root of the pockets and cast rim stress risers at every third pocket and modifications incorporated in the disc design to reduce cost. An earlier design was still serviceable when removed at 2925 hours.

Power turbine wheel at 3831 hours was an early design disc with rim slots partially machined between each blade. Holes drilled at the root of each pocket are sealed with rivets. It is interesting to note that the rim slits cracked through at approximately every third pocket. This wheel was removed from service because of miscroscopic cracks progressing into the disc at the root of the pockets.

The original release burner (not baseline) was removed at 2256 hours and replaced by the baseline lower emission burner. Some material deterioration is evident along with some cracking and hot spots. It's air-cooled igniter was removed at 1002 hours of operation due to erosion of the electrodes. The ignition system used with this igniter was not optimized for energy level.

The baseline burner at 276 hours (Fig. 62) showed the mixer and simple igniter to be in good condition. The burner tube fabricated of 0.035 inch RA-333 and exit of 0.050 RA-333 exhibited distortion. Modifications have been made, and the combustion system is continuing on test.

The regenerator core and seal assembly hot side (Fig. 63) at 2068 hours showed a highly polished seal surface with virtually no wear. The core matrix was in good condition, but the ring gear (second gear) was worn. The cold side of the regenerator assembly (Fig. 64) appears never to have been run.

Significant wear has occurred on both of two ring gear designs, fine pitch (16P) and coarse (12P), Fig. 65. The fine pitch design results in low contact ratio, poor back lash control due to core eccentricity and center distance changes due to temperature differences, but does have low sliding velocities. Pinion wear rate is nil. The coarse pitch design does result in a higher contact ratio and tolerates core eccentricity better, but as a result of higher sliding velocities causes moderate pinion wear. These gears operate in a hostile environment, unlubricated and at 500°F. Ring gear material is generally cast iron and pinions are of 8640, 1046 tufftrided, nitrided, etc..

Engine housing (Fig. 66) is of a three-piece construction as a laboratory convenience. Housing material is high silicon cast iron, MS 4062. The insulation retaining sheetmetal is FeAl alloy. The only significant deterioration in this assembly was development of some cracks in the housing's regenerator platform.

The burner vortex at 3900 hours shows distress only at an area of weld repair, made before it was first put into service. This is an iron base, austenitic investment casting.

In conclusion, based on past experience with gas turbines in both test cells and vehicles, the endurance evaluation procedure being used yields a valid accelerated life test. Acceleration endurance testing of 2000 hours is sufficient durability for all the turbine components.

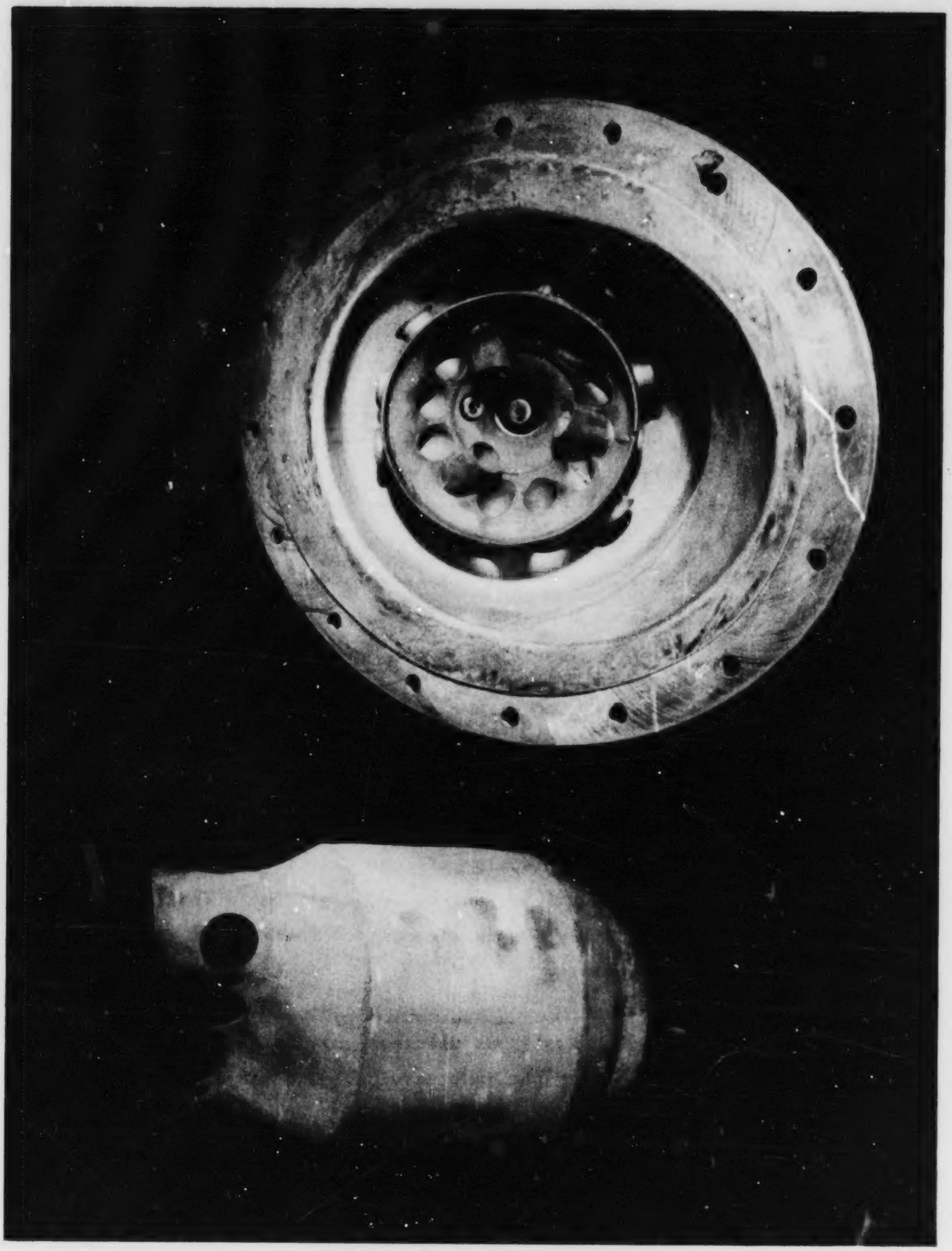


Fig. 62   Baseline Burner (276 Hours)

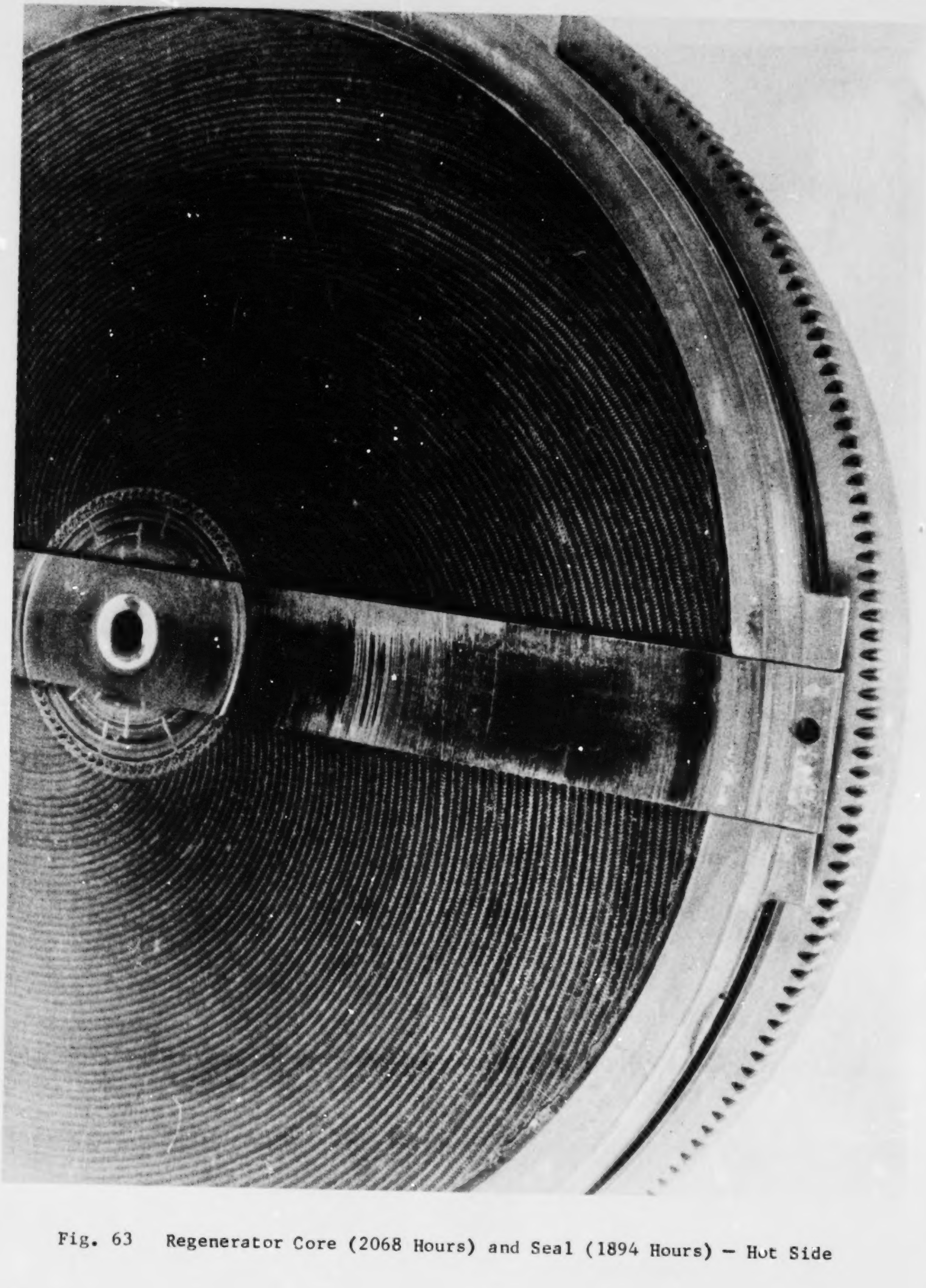


Fig. 63 Regenerator Core (2068 Hours) and Seal (1894 Hours) – Hot Side

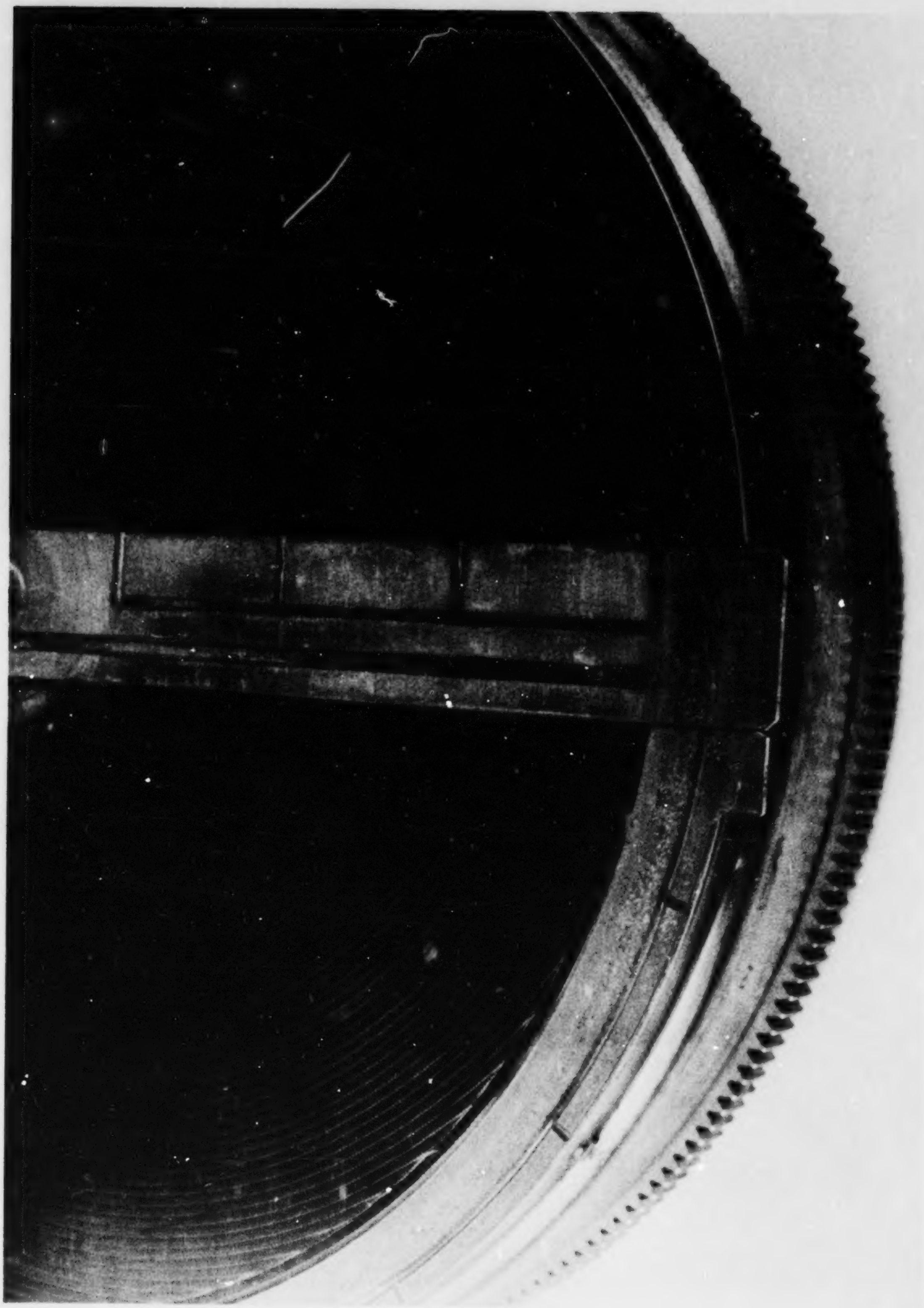


Fig. 64 Regenerator Core (2068 Hours) and Seal (1894 Hours) – Cold Side

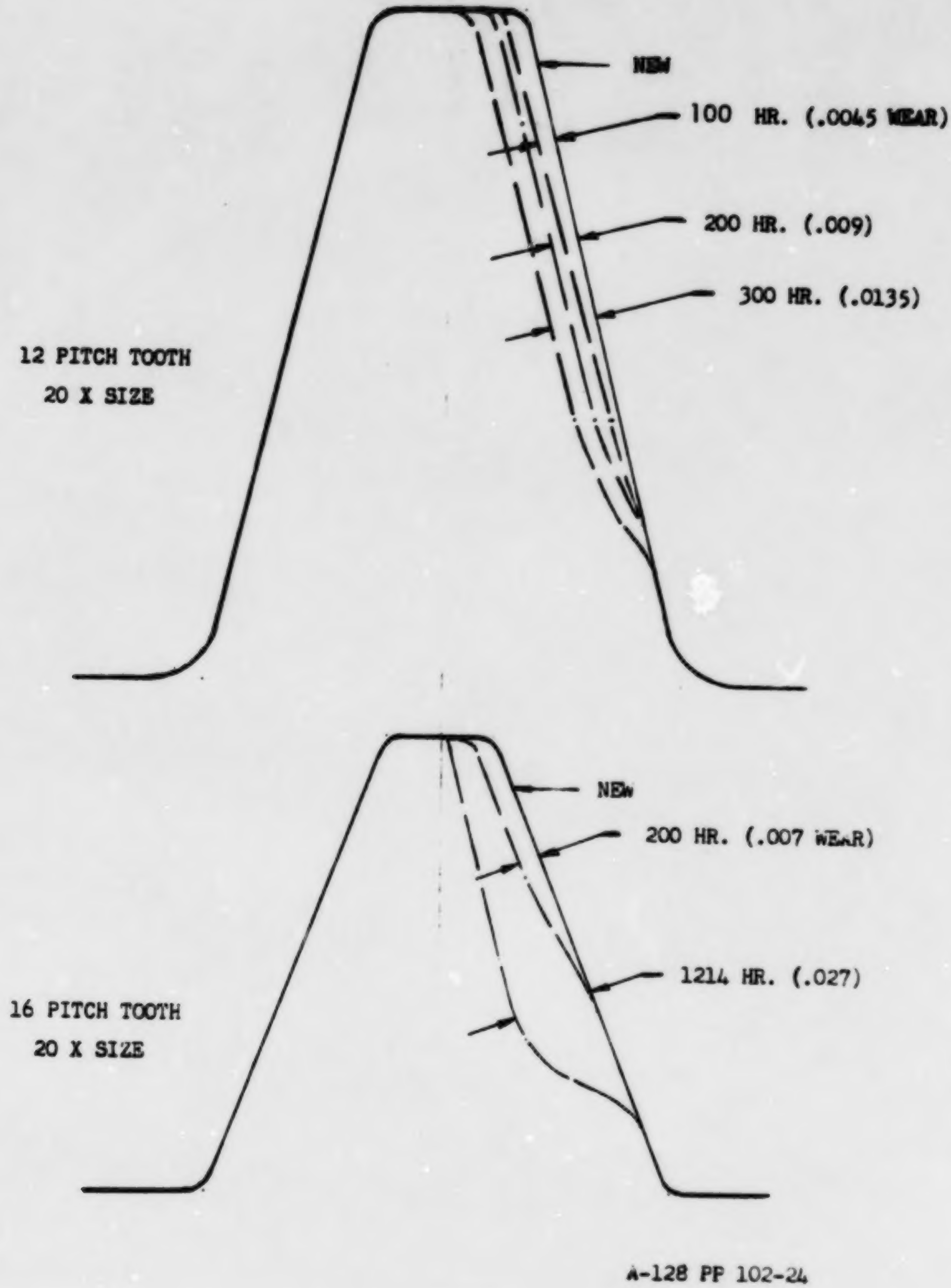

NEW
100 HR. (.0045 WEAR)
200 HR. (.009)
300 HR. (.0135)
12 PITCH TOOTH
20 X SIZE
NEW
200 HR. (.007 WEAR)
1214 HR. (.027)
16 PITCH TOOTH
20 X SIZE
A-128 PP 102-24

Fig. 65 Regenerator Ring Gear Endurance Evaluation

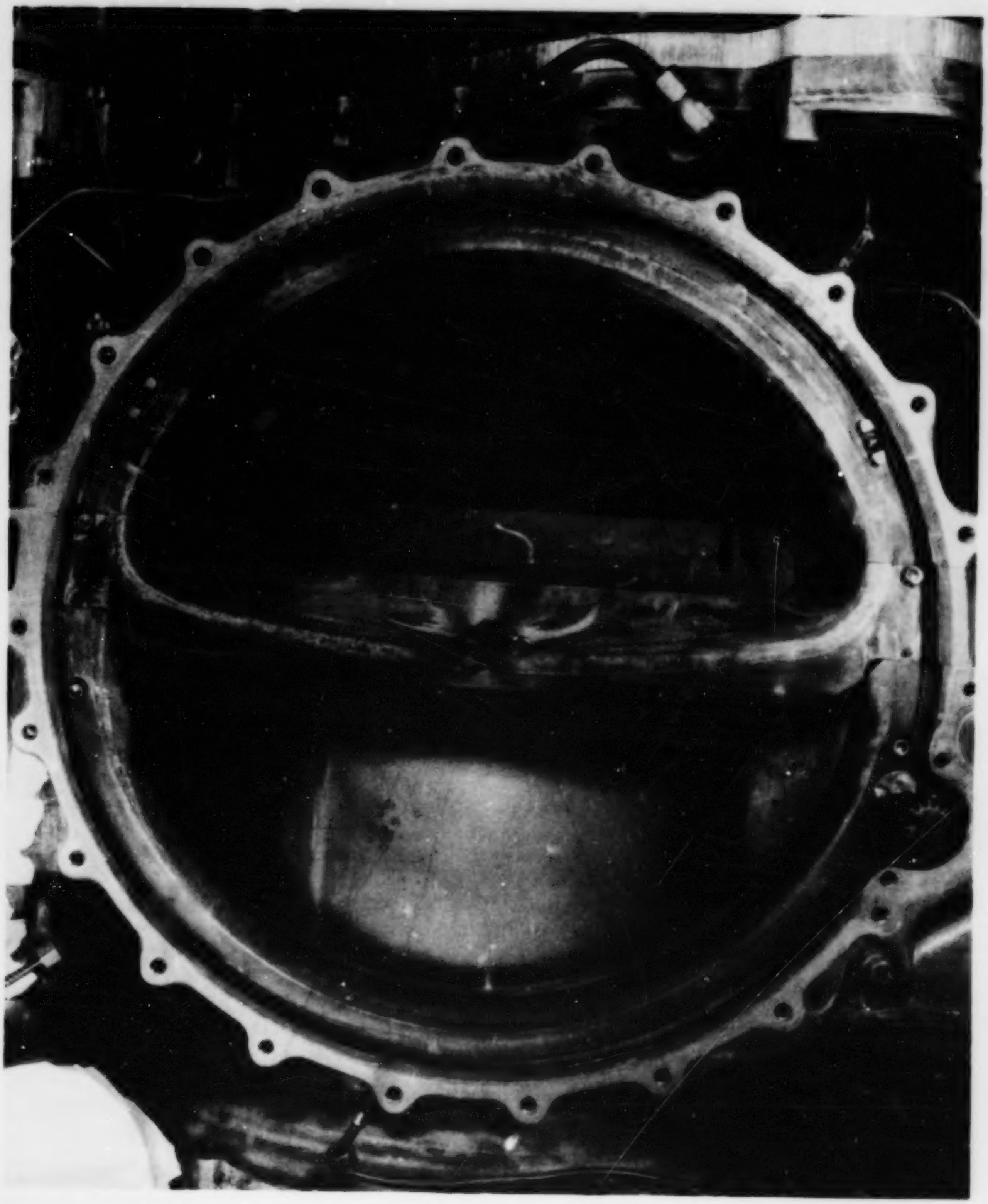


Fig. 66 Engine Housing - Left Side

The Baseline Engine has outstanding durability in critical areas.

Points Clarified during Question/Answer Period

- Chrysler's patent position on the automotive passenger car turbine is strong; however, it has always been company policy to make patents available to others in the industry on a very reasonable license basis. Participation in a Government supported program is not believed to jeopordize Chrysler's proprietary position since, the turbine has quite a way to go and they should be able to keep ahead of the field with advanced developments on their own efforts, if they expect to compete in this industry. Hence, they are willing to share experience and methodology as they go.
- The metal regenerator core uses 430 stainless steel material treated for oxidation resistance. It has 0.003-in corrugations, with a 0.003-in flat strip between corrugations.
- It is not believed that ceramic cores have reached the level of capability of the metal cores; however, as temperatures go up ceramic materials are expected to be the long term answer.
- The EPA specified endurance life is 3500 hours on the EPA duty cycle. Since Chrysler had already started endurance testing on their own, more severe duty cycle when the Baseline program was started, that test was completed. It is believed that 2000 hours on the Chrysler cycle is equivalent to 3500 hours on the EPA duty cycle.
- The odor characteristics of gas turbine vehicles are to be considered in the Baseline Turbine Engine Program.
- Chrysler will report the impact of the engine cost on the price of the vehicle. Some of the details of manufacturing technology and cost reduction may not be reported.
- In the power turbine test package it is very difficult to duplicate the turbine exit flow conditions from the compressor turbine

of an engine; hence, NASA is going to do the best they can and then, through very detailed measurements of the flow, establish the necessary correlation between the test package and the actual engine.

- The test measurements to be made by NASA on these components will be very extensive and detailed; perhaps more so than has ever been made on an automotive turbine such as this.

D. NASA Component Support for Baseline Engine by Jack Heller, Project Manager, and Harold Rohlik, Chief, Turbodrive Branch, NASA, Lewis Research Center, Cleveland, Ohio

Gas Turbine Program: One of NASA's prime activities is to seek improvements in the EPA Upgraded Engine aerodynamic components. To quickly evaluate a variety of candidate cycles and component designs, an existing NASA turbofan jet engine design and off-design computer program was modified to simulate the two-shaft automotive gas turbine engine. The basic GENENG program is described in NASA TN D-5662, dated February 1972.

Early computer results, based on an engine design pressure ratio of 5.0, indicated a need for a number of developmental tasks in the mechanical components of such a design. These tasks were considered beyond the scope of EPA's current engine/vehicle demonstration program. The computer program is now being re-run to reflect designs that meet the current specifications of the upgraded engine as presented in Section V-C above.

Specific areas wherein the NASA will contribute include the aerodynamic design of the three rotating components, a flow analysis of the ducting between components, and individual component performance testing.

The NASA experimental test arrangement, areas of concern, contributions, and specific activities are shown in Fig. 67. Figures 68 and 69 show details of the compressor and turbine test rigs, respectively. Figure 70 summarizes important details of the NASA preliminary designs on the three rotating components.

AREAS OF CONCERN IN CURRENT ENGINE

HIGH SFC AT LOW POWER
COMPONENT PERFORMANCE UNCERTAINTY
POWER TURBINE STATOR CLEARANCE LOSS
DUCT LOSSES
APPARENT HEAT LOSS

NASA CONTRIBUTIONS

CYCLE ANALYSIS
AERODYNAMIC DESIGN
FLOW ANALYSIS
COMPONENT TESTING

SPECIFIC ACTIVITIES

EVALUATE CHRYSLER COMPONENTS
CORRELATE COMPONENT & ENGINE DATA
DESIGN NEW COMPONENTS
EVALUATE NEW COMPONENTS

EXPERIMENTAL EQUIPMENT

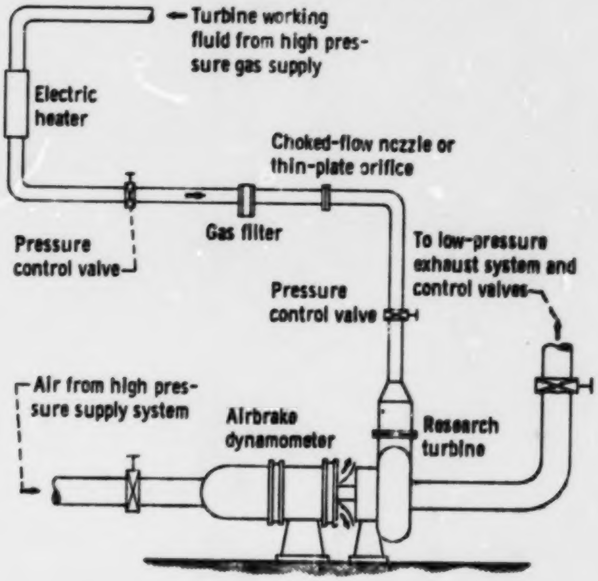

Turbine working fluid from high pressure gas supply
Electric heater
Choked-flow nozzle or thin-plate orifice
Gas filter
Pressure control valve
To low-pressure exhaust system and control valves
Pressure control valve
Air from high pressure supply system
Airbrake dynamometer
Research turbine

Fig. 67 NASA Participation in Baseline Program

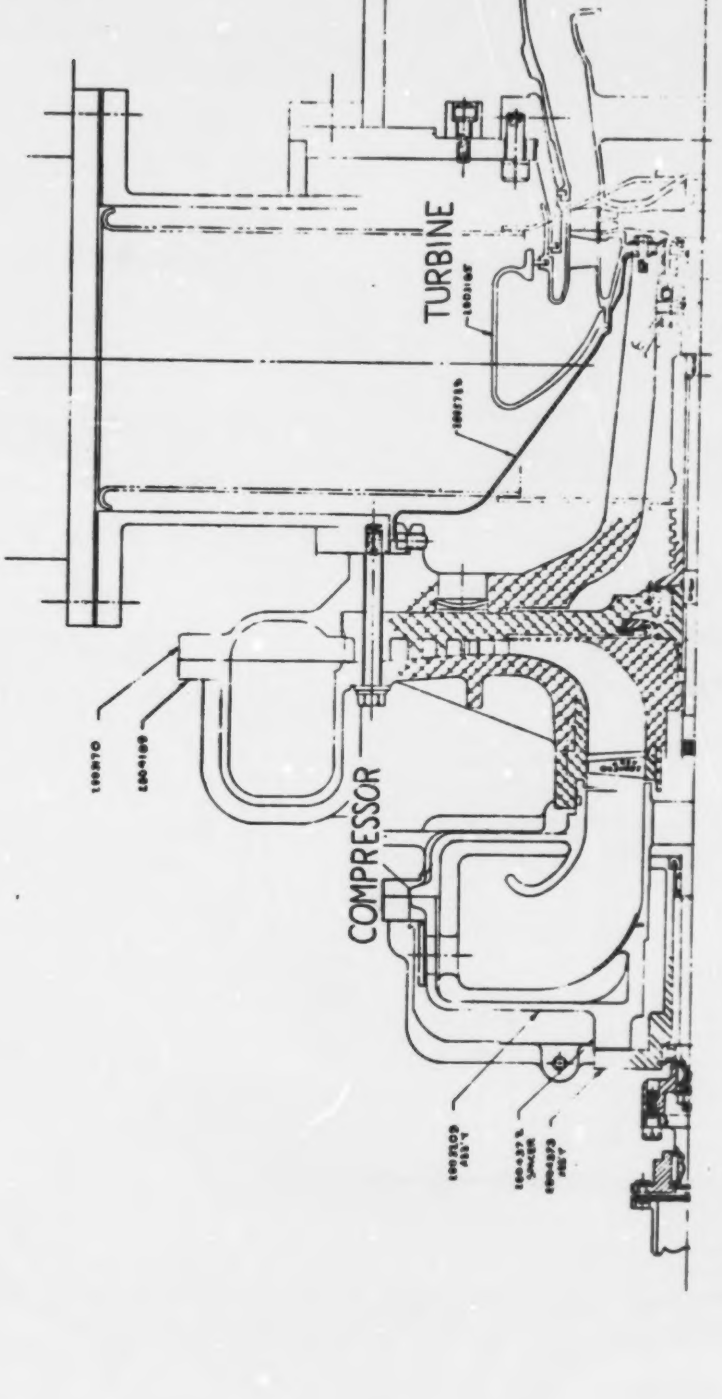

TURBINE
COMPRESSOR

Fig. 68 Compressor Test Rig

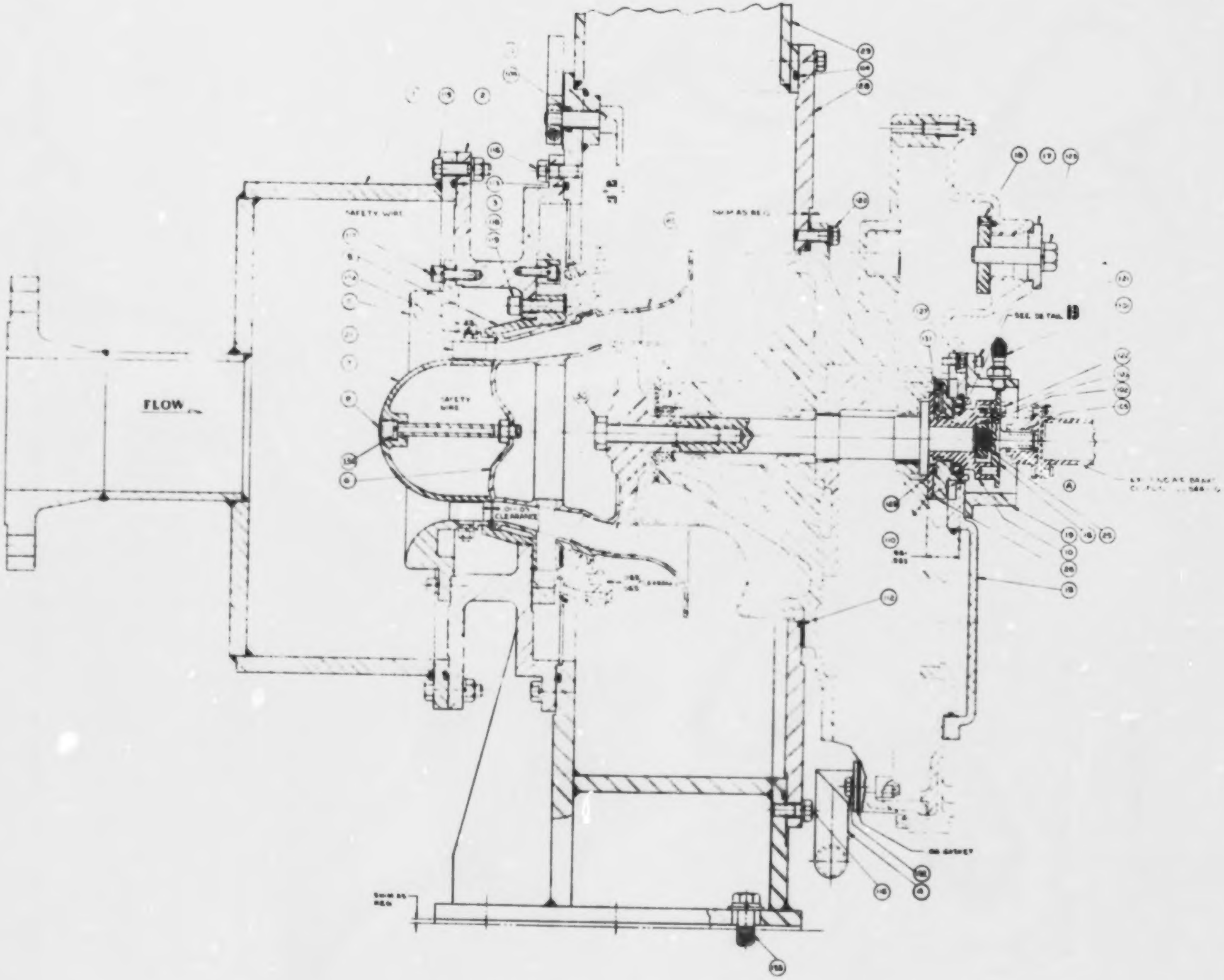
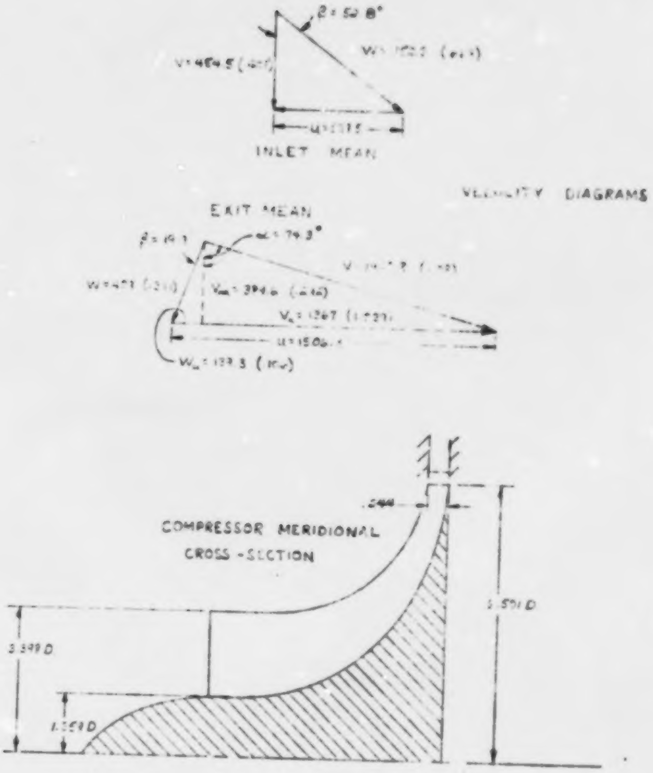
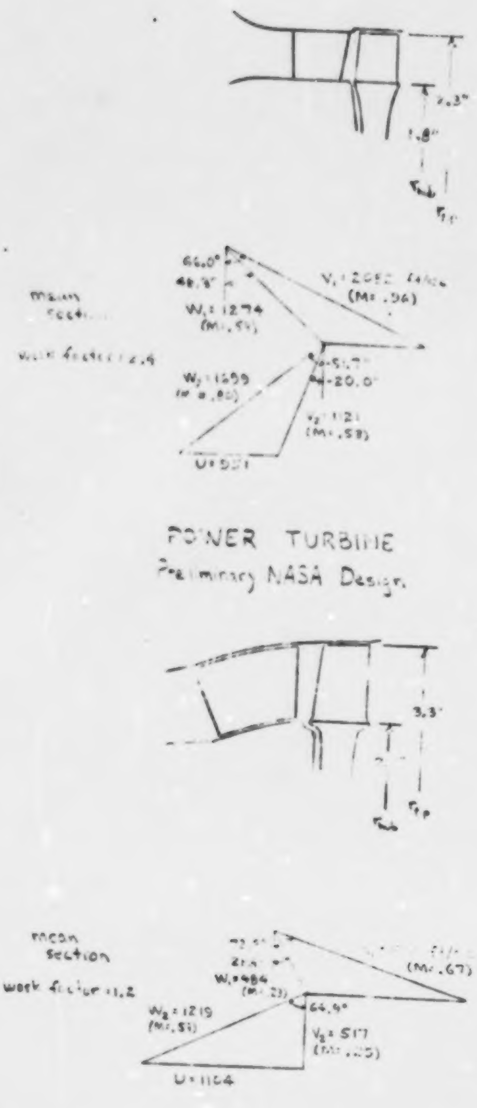

FLOW
SAFETY WIRE
SAFETY WIRE
CLEARANCE
SEE DETAIL B
OR GASKET

Fig. 69 Turbine Test Rig

ENGINE CHANGES

UN-AUGMENTED POWER, HP	150	TO	120
MAX. FLOW, LB/SEC	2.27	TO	1.60
MAX. TEMPERATURE, °F	1850	TO	1925
GAS GENERATOR SPEED, RPM	[illegible]	TO	53,132


β = 52.8°
W = 1022
U = 1115
INLET MEAN
VELOCITY DIAGRAMS
EXIT MEAN
α = 74.3°
Vm = 394.6
Vθ = 1267
U = 1506
COMPRESSOR MERIDIONAL CROSS-SECTION
.244


2.3"
1.8"
r hub
r tip
66.0°
46.8°
V1 = 2052
(M = .96)
mean section
W1 = 1274
(M = .59)
work factor = 2.4
W2 = 1699
-51.7°
-20.0°
V2 = 1121
(M = .58)
U = 951
POWER TURBINE
Preliminary NASA Design
3.3"
r hub
r tip
mean section
work factor = 1.2
(M = .67)
W1 = 484
W2 = 1219
(M = .53)
64.9°
V2 = 517
(M = .25)
U = 1104

Reproduced from best available copy.

Fig. 70 Key Details of NASA Preliminary Design of Aerodynamic Components

Points Clarified during Question/Answer Period

- Calculations show that the component improvements should result in a 40% reduction in specific fuel consumption at about 20 HP; Chrysler people estimate about a 50% reduction at idle; about 30% reduction at 60% speed, and about 50% reduction over the Federal Driving Cycle.
- Changes are contemplated only in the turbomachinery elements, interconnecting flow passages, and a few details of ducting at burning exit and in and out of regenerator. The regenerator, running gear, and the engine will be left essentially unchanged.

E. Solar Low Emission Burner for Baseline Gas Turbine Program by David White, Project Manager, Solar Division of International Harvester Co., San Diego, California

The intent is to develop a low emission combustion system for installation and demonstration in the Baseline Gas Turbine Engine. The combustor is based on the design concepts of the Solar JIC-3 low emission combustor, developed under a previous EPA program. Specifically, the combustor should:

- be capable of operating over the entire engine cycle
- meet one half or less of the 1976 Federal Automotive Emissions Standard
- meet the combustor/engine interface requirements

The program has been divided into three distinct phases. Phase I encompasses the preliminary design, fabrication, and test optimization of models of the key combustor components such as the primary zone, the variable area primary ports, and the ignition system. In Phase II, a prototype, full-scale combustor, including all necessary cooling requirements and a variable area mechanism, will be designed and built. Control of the variable area ports will be accomplished manually in this phase, rather than by a control system, using sensors and remote actuation. This combustion system will be rig tested over a simulated Federal Driving Cycle and modified as necessary to conform to the emission goals. The final phase covers the construction and proof testing of a combustion system suitable for installation in a gas turbine vehicle.

The bulk of the combustor testing to date has been concerned with the performance comparison of two candidate systems; one incorporating a conventional can combustor (Fig. 71), the other employing a novel folded annular approach (Fig. 72). These two systems are being evaluated with respect to emissions (Fig. 73), complexity of variable geometry mechanization, and packaging suitability (Fig. 74). The Phase II combustion system is now defined as a 10-inch diameter can-type; preliminary design of the overall system is underway.

Points Clarified during the Question/Answer Period

- When 1/2 of the fuel injectors were turned off, no quenching effect on the CO and UHC was experienced. This is believed to be due to the very rapid mass transport between the impinging jets.

F. AiResearch Integrated Control System for the Baseline Program, by Harvey LeFevre, Project Leader, Chrysler Corporation, and Leon Lewis, Project Manager, Garrett-AiResearch, Torrance, California

Present Baseline Engine Control: The Baseline Engine control system is hydromechanical, open-loop. These controls have been used because of their simplicity, reliability, and low cost. (See Figures 75 and 76).

Fuel metering is governed for steady state operation, while acceleration fuel flow is scheduled. For decelerations, the fuel is shut off and a relight occurs at the lower required speed.

The power turbine nozzles are positioned by a hydromechanical actuator (Figure 77). It provides two idle positions, part power scheduling, a maximum power position and a braking position, as determined by control logic.

The Baseline Engine is protected in the vehicle by a start safety system. (Figure 78). The engine cannot be started with the transmission in gear. If oil pressure is obtained within 5 seconds and a burner light-off within

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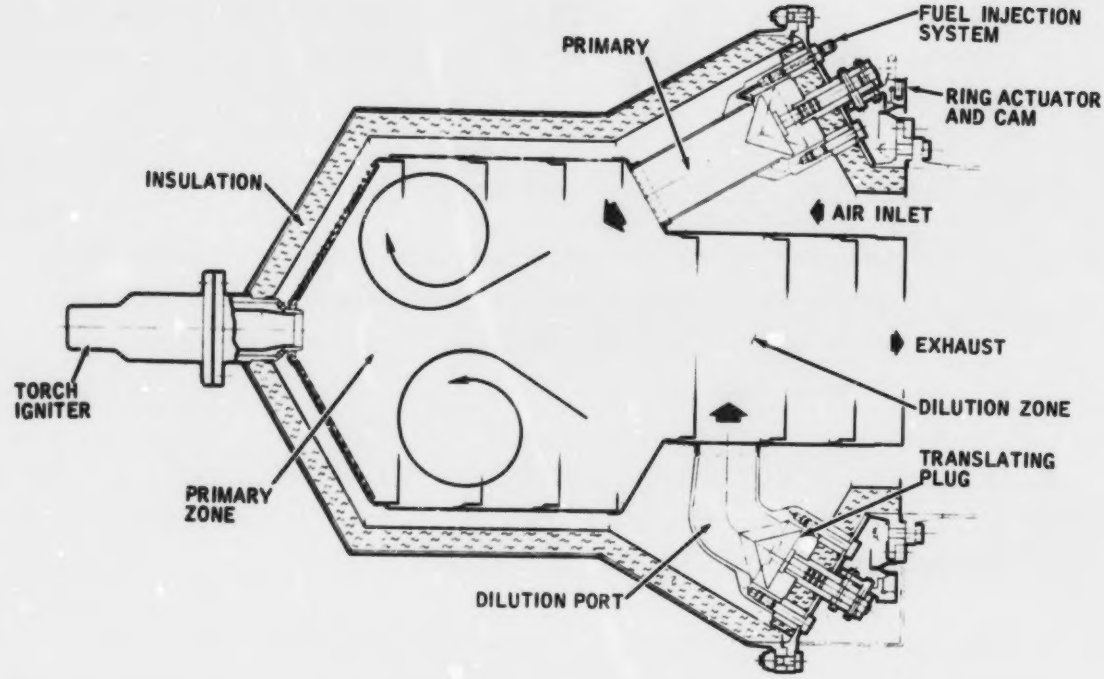
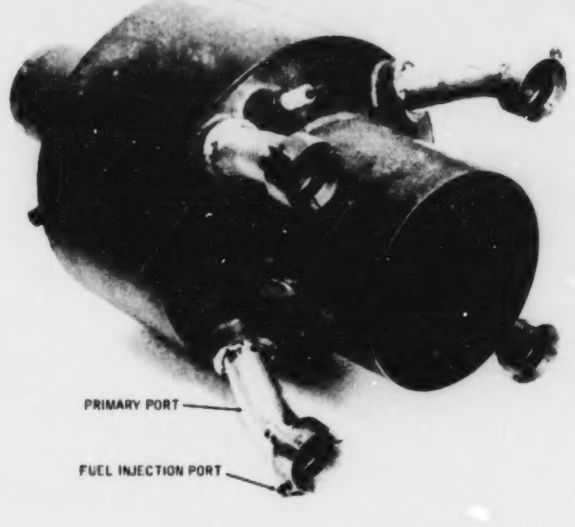
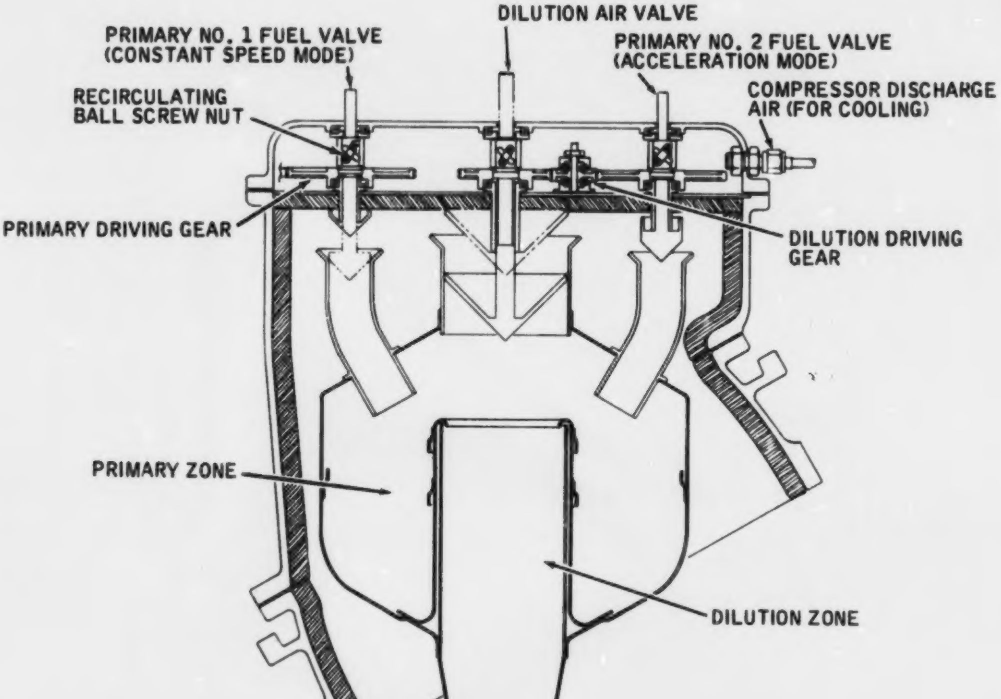

FUEL INJECTION SYSTEM
PRIMARY
RING ACTUATOR AND CAM
INSULATION
AIR INLET
EXHAUST
TORCH IGNITER
DILUTION ZONE
TRANSLATING PLUG
PRIMARY ZONE
DILUTION PORT

Fig. 71 Typical Can Combustor, Variable Area Approach


PRIMARY PORT
FUEL INJECTION PORT

Folded Annular Combustor (JIC) Primary Zone Model


DILUTION AIR VALVE
PRIMARY NO. 1 FUEL VALVE (CONSTANT SPEED MODE)
PRIMARY NO. 2 FUEL VALVE (ACCELERATION MODE)
RECIRCULATING BALL SCREW NUT
COMPRESSOR DISCHARGE AIR (FOR COOLING)
PRIMARY DRIVING GEAR
DILUTION DRIVING GEAR
PRIMARY ZONE
DILUTION ZONE

Typical Folded Annular Combustor (JIC) Variable Area Approach

Figure 72

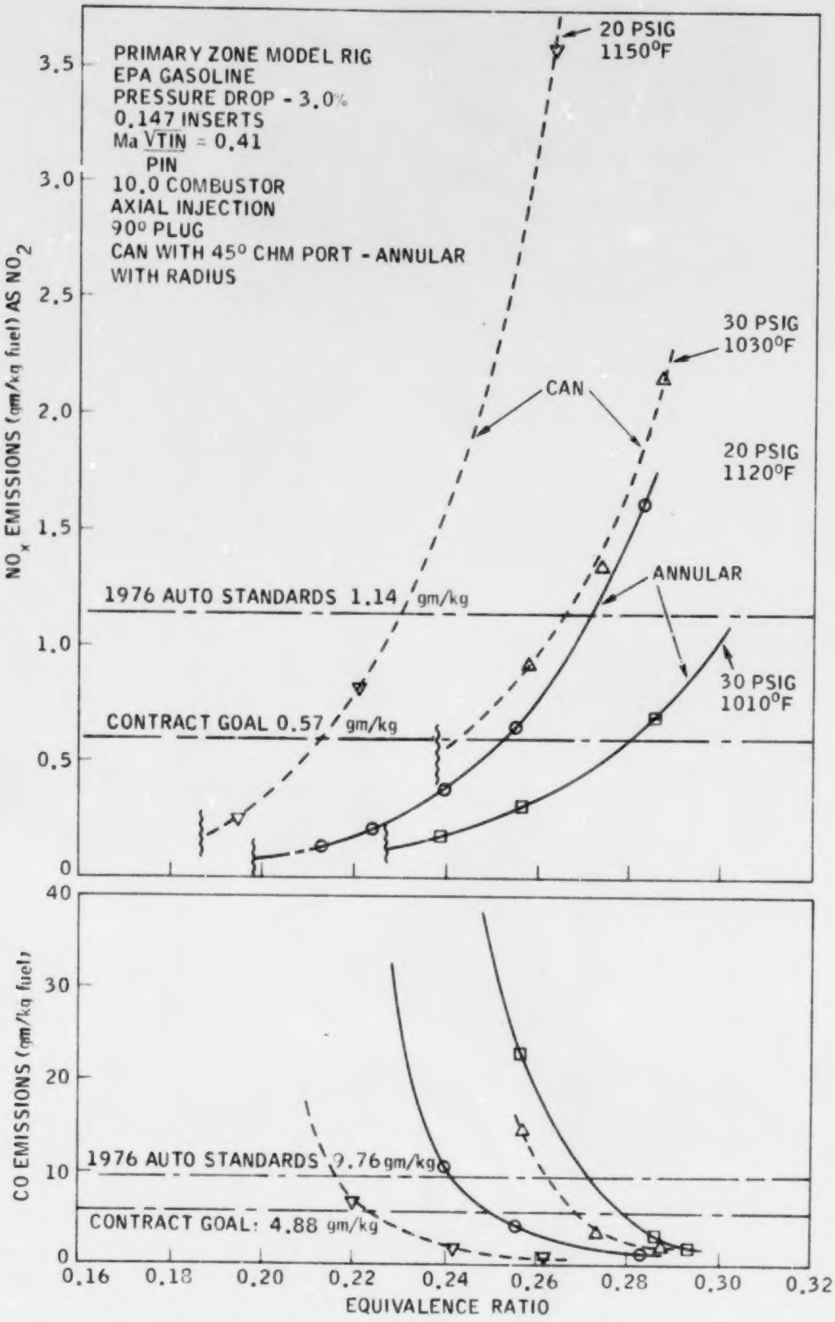


Fig. 73 Primary Zone Model Emissions Characteristics 10-Inch Diameter Can Versus Axial Combustor

	CAN	FOLDED ANNULAR
BACKGROUND EXPERIENCE	EPA - AAPS Contract No. 68-04-0016 JIC - 3 Combustor	None.
EMISSIONS	Meets Program Goals Over A Narrow Range Of Operating Conditions.	Primary Zone Models Generally Superior To Can In Low Emissions Rangewidth.
COOLING REQUIREMENTS	Conventional Techniques.	Cooling Problem With Inner Liner - Effects On Emissions.
PACKAGING (Variable Geometry Mechanization)	Difficult To Accomodate Variable Geometry Mechanization Within Conventional Engine Casing Envelopes.	More Amenable For Incorporation Of Variable Geometry Mechanization. Expecially with Single Dilution Port.

Fig. 74 Combustor Configurations (JIC) — Comparison Chart

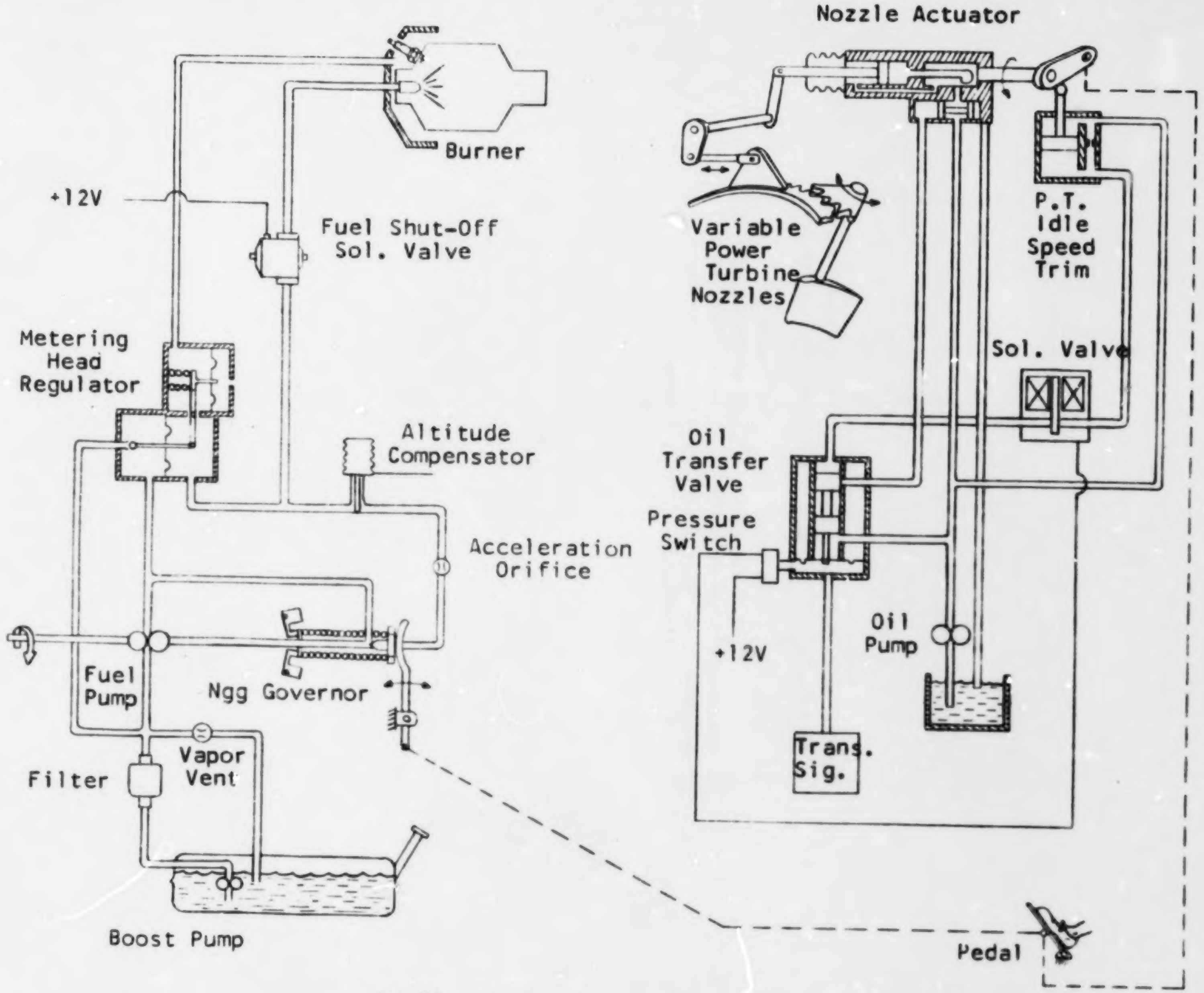

Nozzle Actuator
Burner
+12V
Fuel Shut-Off Sol. Valve
Variable Power Turbine Nozzles
P.T. Idle Speed Trim
Metering Head Regulator
Sol. Valve
Altitude Compensator
Oil Transfer Valve
Pressure Switch
Acceleration Orifice
Oil Pump
+12V
Fuel Pump
Ngg Governor
Trans. Sig.
Filter
Vapor Vent
Boost Pump
Pedal

Fig. 75 Baseline Engine Control System

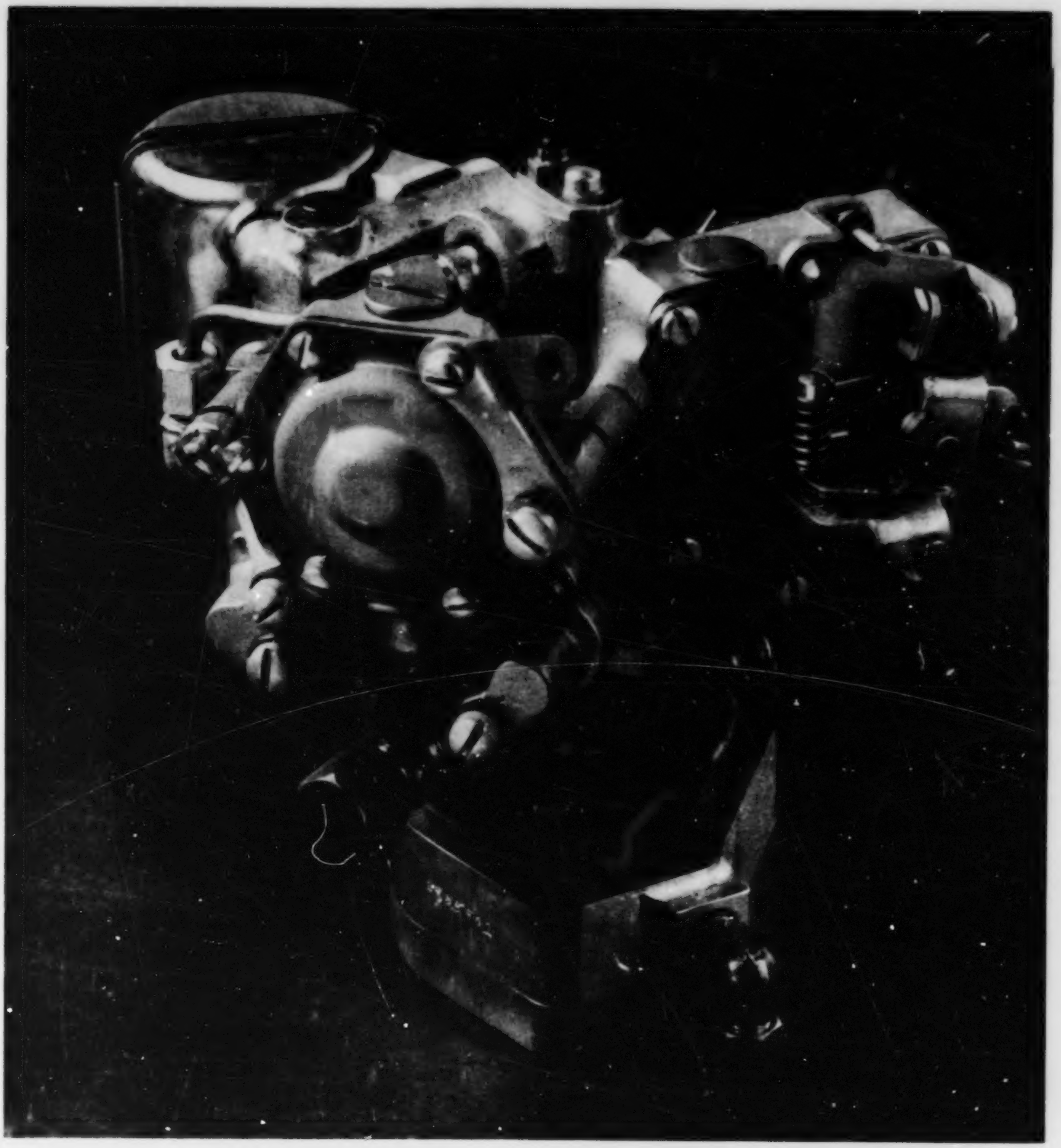


Fig. 76 Hydromechanical Fuel Control

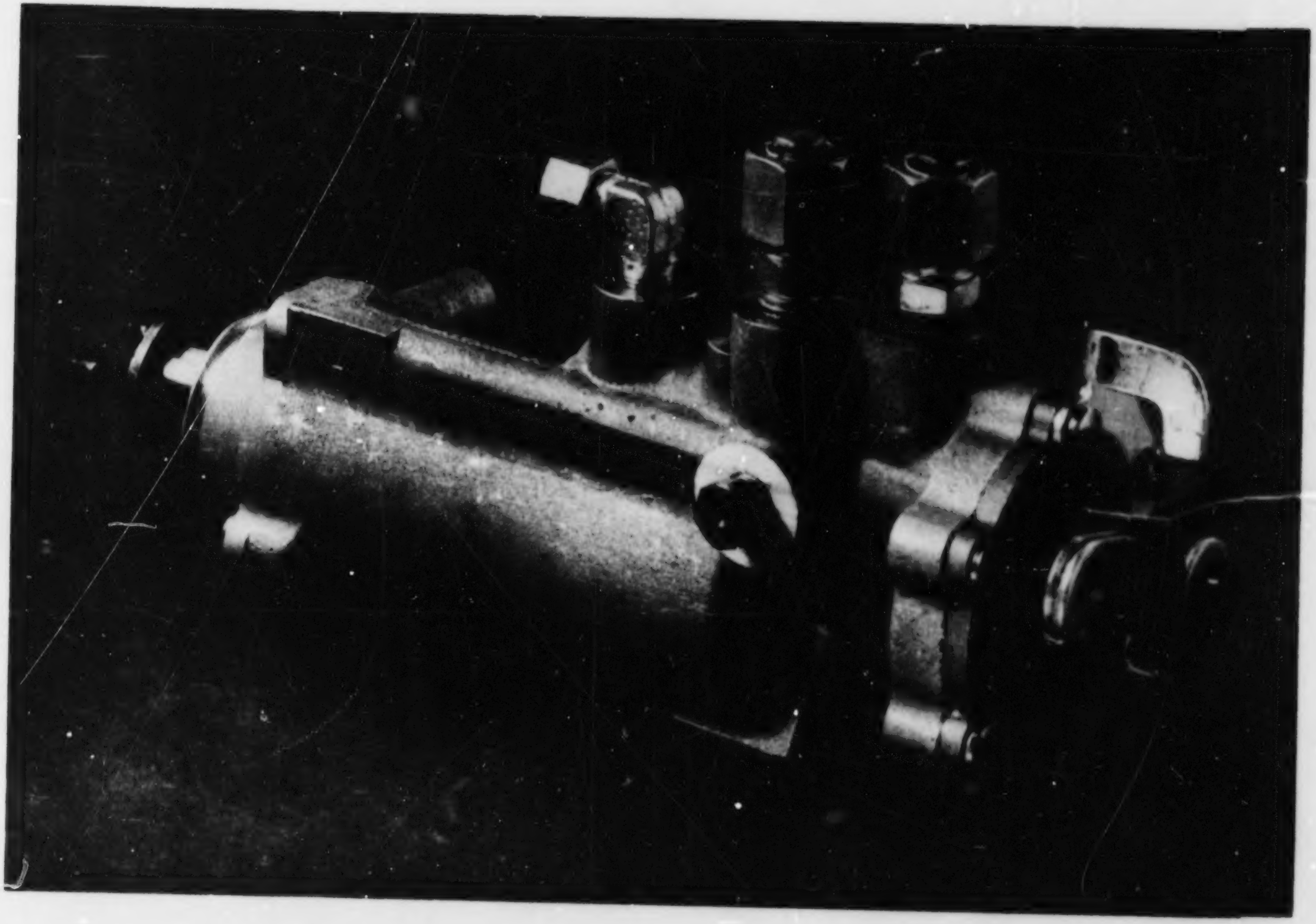


Fig. 77 Hydromechanical Nozzle Actuator

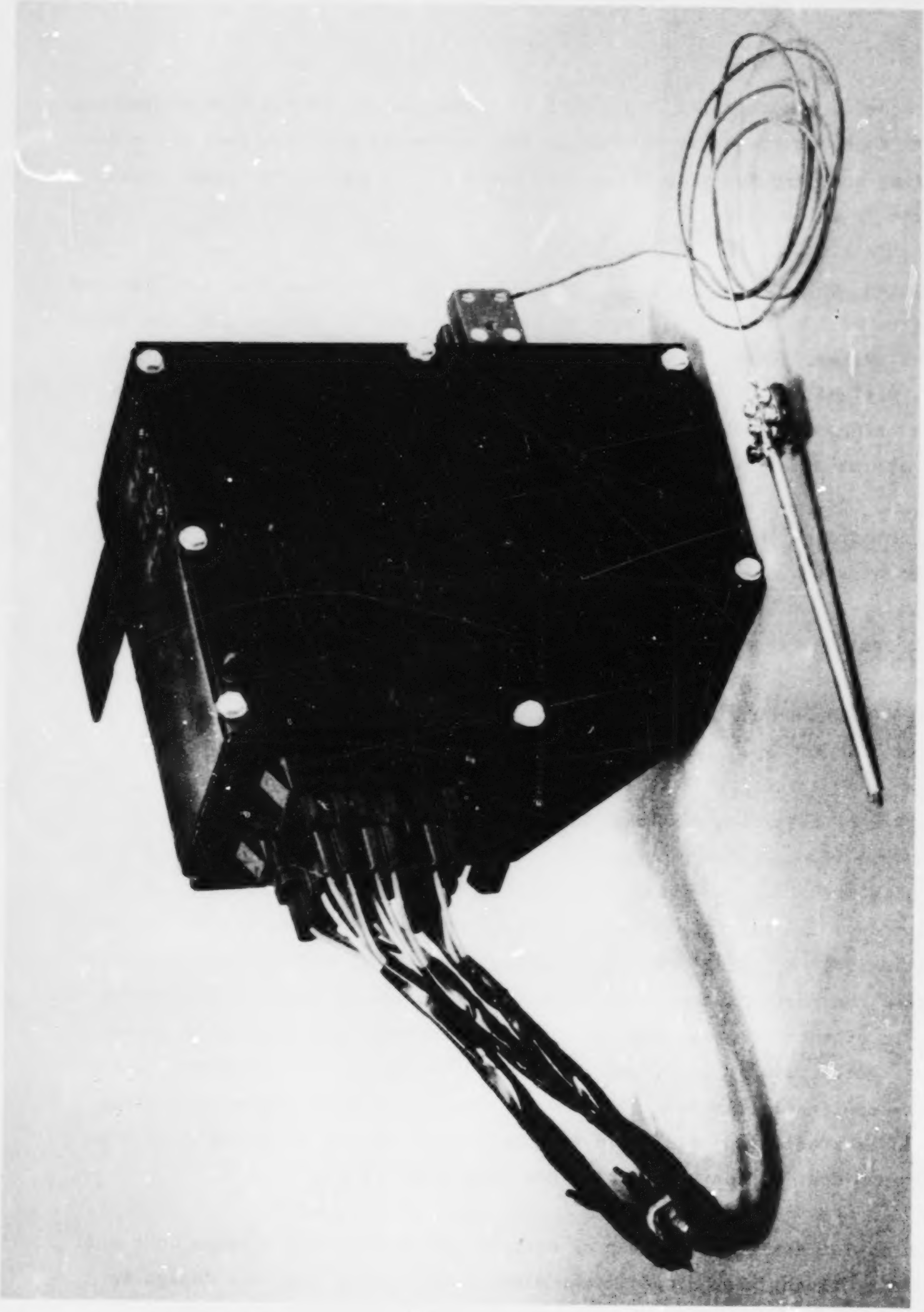


Fig. 78 Start Safety Box

8 seconds, a successful "run" will be accomplished, provided that cranking time does not exceed 20 seconds or that an overtemperature does not occur during starting for a duration of 2 seconds or longer. The start system logic is shown in Fig. 79.

Program to Develop Integrated Control: It is recognized that the Upgraded Engine will probably require a more accurate control system than the Baseline system. The expanded control requirements for the Upgraded Engine, ie. variable inlet guide vanes, a variable burner, water injection, and provisions for diagnostics, will require extensive cost-benefit analysis to arrive at an optimum control system.

An integrated control system will be designed for the Upgraded Engine on a subcontract awarded to Garrett Corporation/AiResearch Division. This control system will be optimized for fuel economy, low emissions, good vehicle performance, low manufacturing cost, and reliability. The program plan and schedule for the 20-month period of this subcontract are shown in Fig. 80. This schedule runs concurrent with development activity for the Upgraded Engine by Chrysler.

Figure 81 illustrates schematically the conceptual design of the overall control system. The program plan has been developed around this approach and is structured to provide a cost-effective design capable of mass production. The initial approach is based upon an electronic computer that is fabricated, using large-scale-integration (LSI) microcircuit techniques. Since the costs associated with the basic design of the chip are beyond the scope of this program, analog circuit techniques will be used to implement the control system functions required in the electronic computer. Alternate configurations such as hydromechanical, fluidic, or hybrid systems will be studied and evaluated throughout the program to ensure that the optimum cost-effective approach has been selected.

The system design objectives of optimum performance and minimum cost will be significantly enhanced if the electronic control computer design is compatible with large-scale-integration (LSI) fabrication techniques.

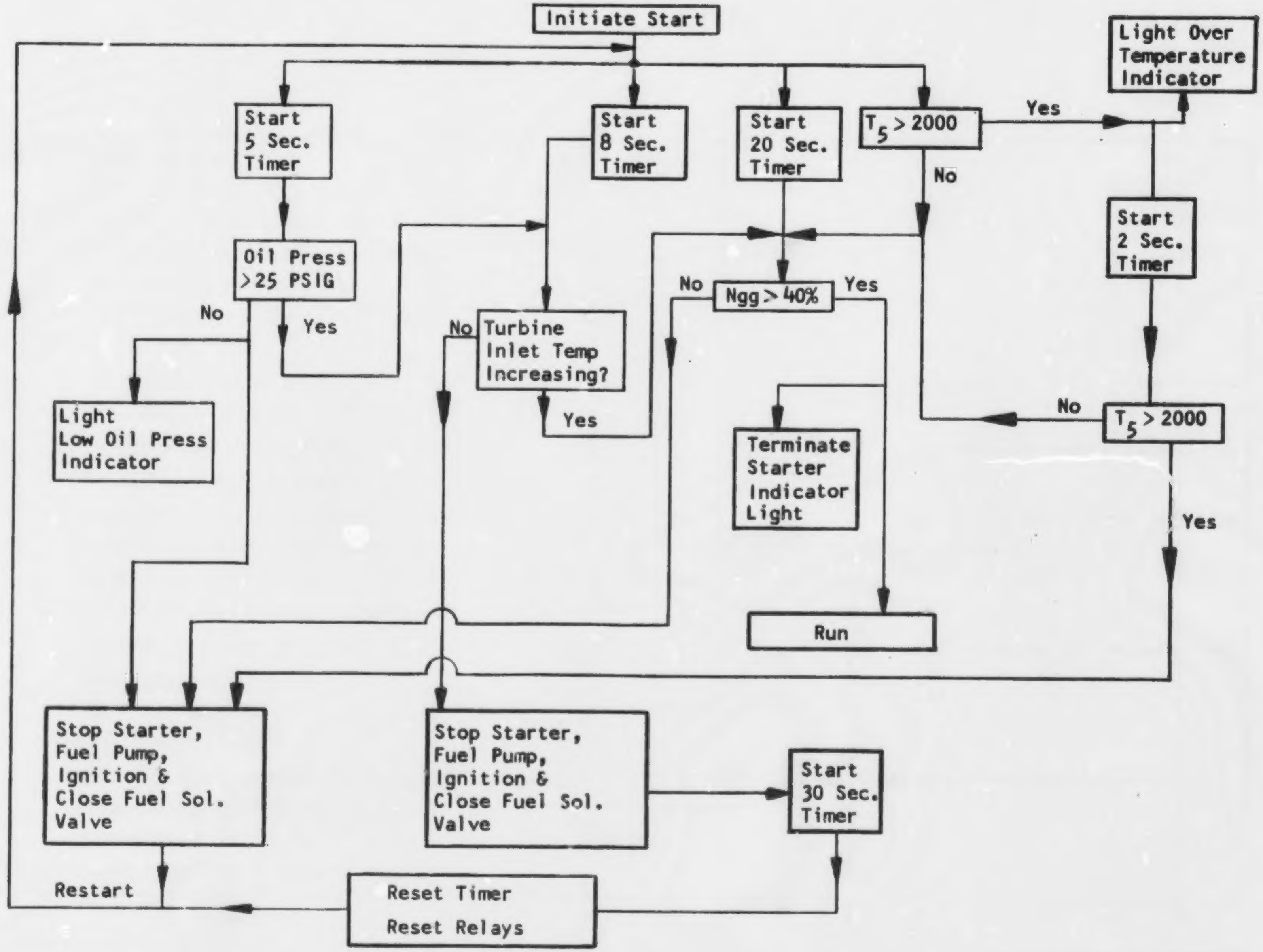

Initiate Start
Start 5 Sec. Timer
Start 8 Sec. Timer
Start 20 Sec. Timer
$T_5 > 2000$
Yes
No
Light Over Temperature Indicator
Start 2 Sec. Timer
Oil Press >25 PSIG
No
Yes
No
Turbine Inlet Temp Increasing?
Yes
No
Ngg > 40%
Yes
No
$T_5 > 2000$
Yes
Light Low Oil Press Indicator
Terminate Starter Indicator Light
Run
Stop Starter, Fuel Pump, Ignition & Close Fuel Sol. Valve
Stop Starter, Fuel Pump, Ignition & Close Fuel Sol. Valve
Start 30 Sec. Timer
Restart
Reset Timer
Reset Relays

Fig. 79 Start System Logic

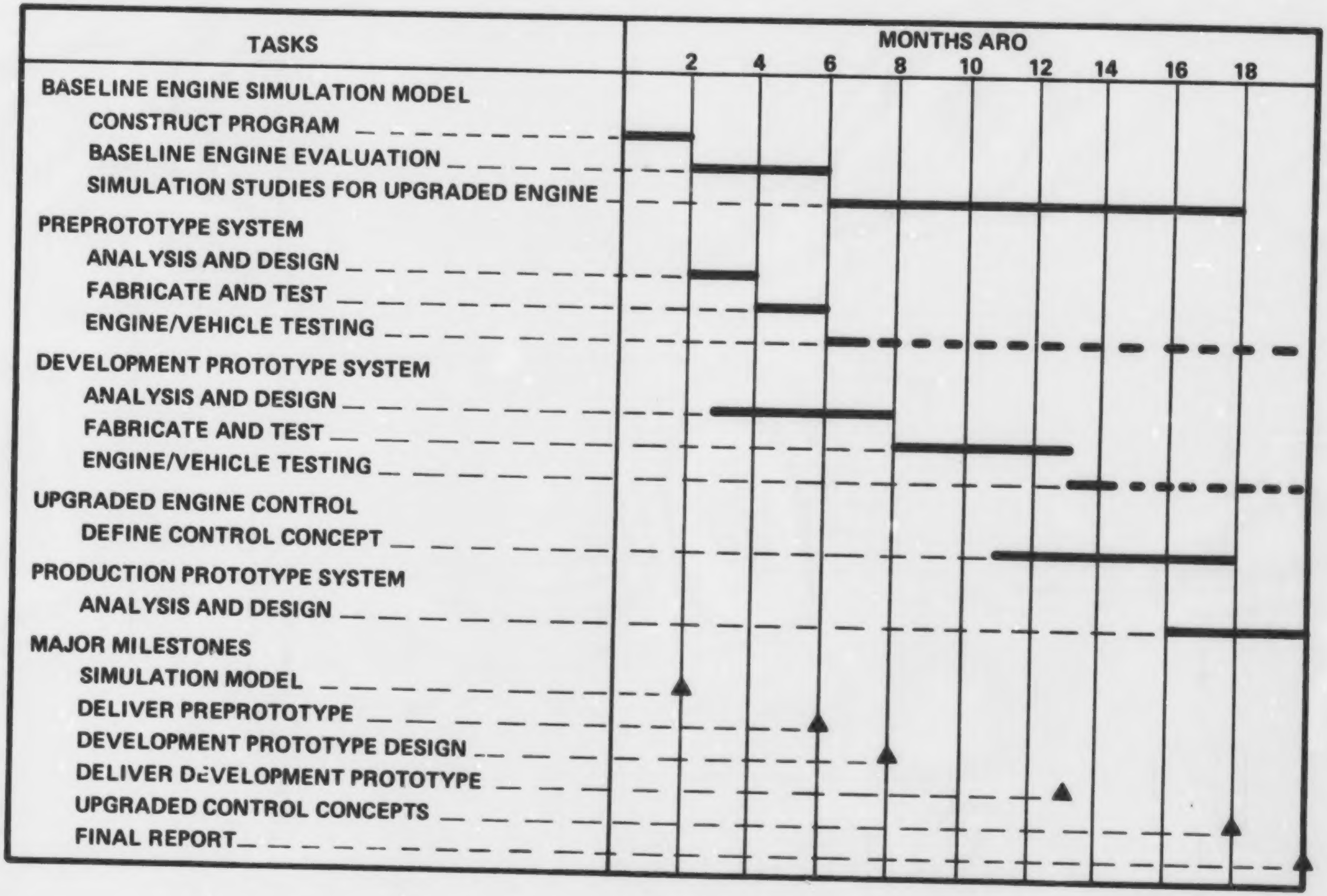


Fig. 80 Integrated Engine Control System Program Plan

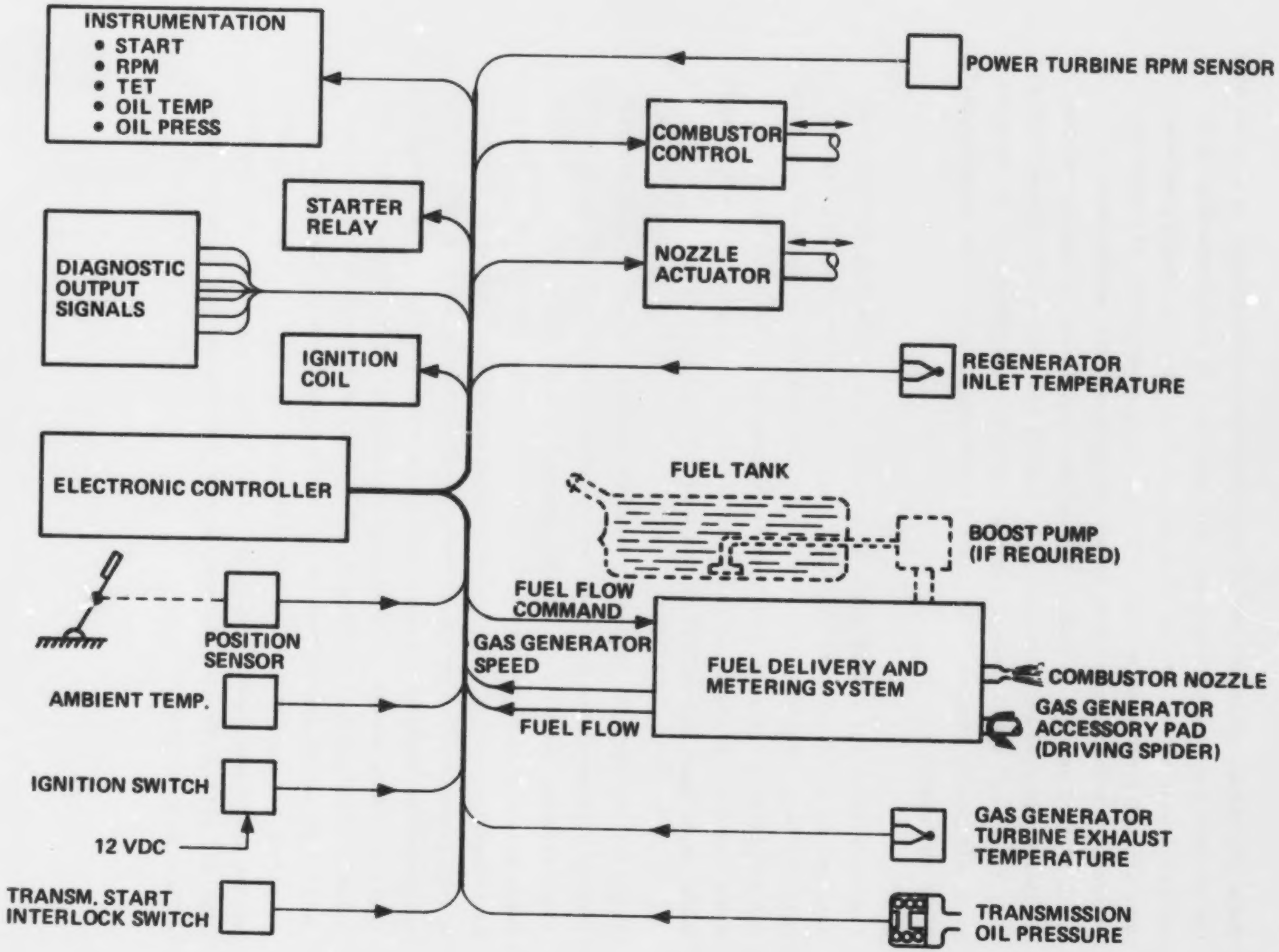

INSTRUMENTATION
• START
• RPM
• TET
• OIL TEMP
• OIL PRESS
POWER TURBINE RPM SENSOR
COMBUSTOR CONTROL
STARTER RELAY
NOZZLE ACTUATOR
DIAGNOSTIC OUTPUT SIGNALS
IGNITION COIL
REGENERATOR INLET TEMPERATURE
ELECTRONIC CONTROLLER
FUEL TANK
BOOST PUMP (IF REQUIRED)
FUEL FLOW COMMAND
POSITION SENSOR
GAS GENERATOR SPEED
FUEL DELIVERY AND METERING SYSTEM
COMBUSTOR NOZZLE
AMBIENT TEMP.
FUEL FLOW
GAS GENERATOR ACCESSORY PAD (DRIVING SPIDER)
IGNITION SWITCH
GAS GENERATOR TURBINE EXHAUST TEMPERATURE
12 VDC
TRANSM. START INTERLOCK SWITCH
TRANSMISSION OIL PRESSURE

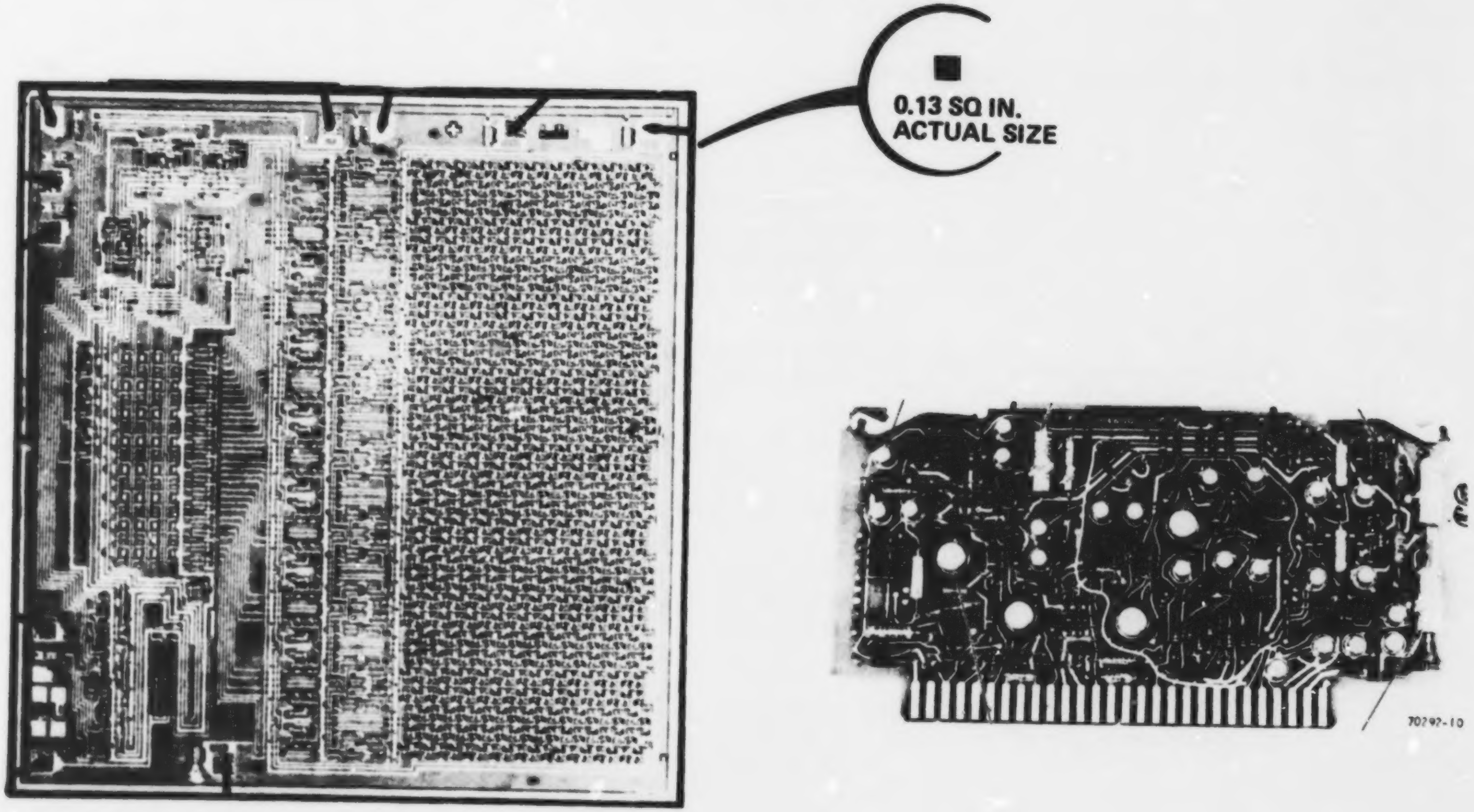
Fig. 81 Fuel Control System Functional Diagram

These techniques allow the use of many hundreds of transistors in a given system at very low production costs. The technique is more compatible with digital computational systems than with analog, since in digital systems most transitor elements act as switches. As a consequence, the absolute performance of each transistor is not critical and the manufacturer's yield of good devices is high. In contrast, for linear or analog systems, the performance of each transistor is significant over a wide dynamic operating range, and the degree of integration that can economically be employed is significantly limited. The limit is essentially set by the manufacturer's yield on components.

Figure 82 shows the relationship of a single chip containing 2330 devices compared to a circuit card utilizing a mixture of analog and digital circuit discrete elements. Chip technology is a relatively new development to the electronics industry, having stemmed from the needs of military and space systems. Dramatic increases in the degree of integration are continuously being made and applied to consumer oriented products.

Compatibility with LSI technology will be assured through a joint program between AiResearch and National Semiconductor Corporation (NSC). In this joint program, NSC will review the proposed controller functional requirements at all stages and make a determination of the feasibility of LSI mechanization. Their method of determination will be to examine the required functions from an input-output configuration standpoint and then to mechanize the proposed computer onto an in-house computer. This computer takes an analog system mechanization and translates it into a digital equivalent. The translated system is a dedicated mechanization to the particular application and represents the minimum component arrangement. The resultant arrangement is then partitioned to the chip level and potential system cost identified. Figure 83 illustrates schematically the functions that NSC will perform in the program and demonstrates the iterative nature of the joint program.

LSI AND DISCRETE


0.13 SQ IN.
ACTUAL SIZE
70292-10

RANDOM ACCESS STORAGE, PN 944114 (2330 DEVICES)

TYPICAL PRINTED CIRCUIT CARD WITH DISCRETE COMPONENTS

Fig. 82 Typical Technology Programs

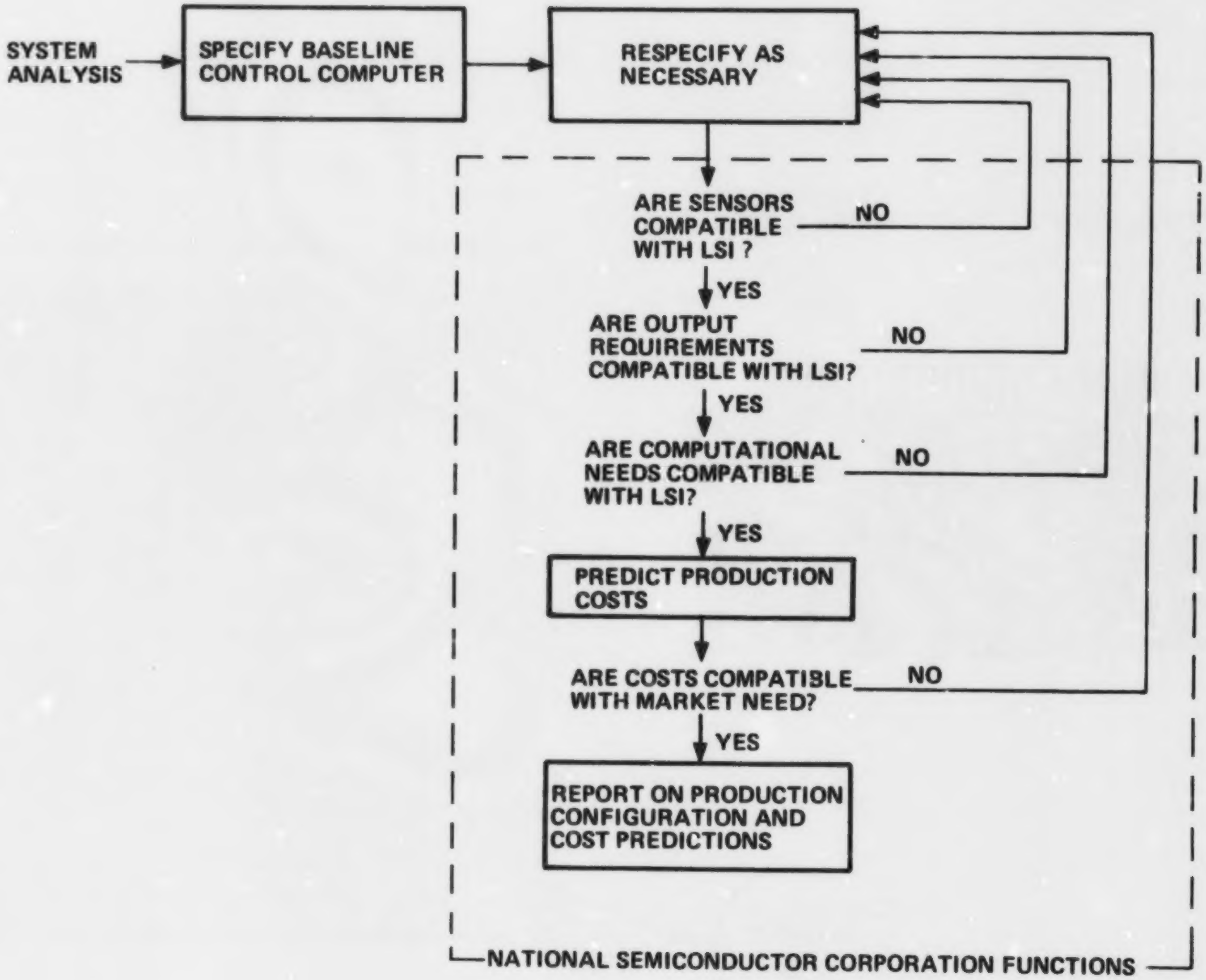

SYSTEM ANALYSIS
SPECIFY BASELINE CONTROL COMPUTER
RESPECIFY AS NECESSARY
ARE SENSORS COMPATIBLE WITH LSI ?
NO
YES
ARE OUTPUT REQUIREMENTS COMPATIBLE WITH LSI?
NO
YES
ARE COMPUTATIONAL NEEDS COMPATIBLE WITH LSI?
NO
YES
PREDICT PRODUCTION COSTS
ARE COSTS COMPATIBLE WITH MARKET NEED?
NO
YES
REPORT ON PRODUCTION CONFIGURATION AND COST PREDICTIONS
NATIONAL SEMICONDUCTOR CORPORATION FUNCTIONS

Fig. 83 AiResearch/National Semiconductor Corporation Program

Points Clarified during Question/Answer Period

- The dollar value of the Integrated Control System contract is $220,000.
- The system is designed to handle the types of fuel found in the country's transportation complex including methanol, No. 1 diesel fuel and gasoline. The gas turbine is a multi-fuel engine.

G. Pratt and Whitney, Florida, Low Cost Turbine Wheel Manufacturing Development, by Marvin Allen, Project Manager, Pratt and Whitney, Palm Beach, Florida

The major unknown in estimating the cost of the gas turbine engine is the manufacturing cost of the rotor. It was assumed that, at the 1,000,000 unit annual rate, high-ductility, close-tolerance forging techniques would be used to produce the impeller and turbine wheels to nearly finished dimensions from the relatively expensive materials specified. Several proprietary versions of the basic forging techniques have been, and are being developed by United Aircraft for current military aircraft engine programs. The basic United Aircraft patented process, developed and reduced to practice at the Florida Research and Development Center, is referred to as the GATORIZING^{TM} forging process.

This process differs from previous hot isothermal forging methods in that the temperature and forging rate are controlled either to produce a condition of superplasticity in the material being forged, or to maintain a condition of superplasticity in material previously placed in that condition by special processing techniques. Exploiting the superplastic state of the material allows forging of complex, contour shaped rotors to extremely close tolerances, which drastically reduces the input weight of the material required and reduces machining costs. In addition, smaller, less costly forging equipment than that required for conventional superalloy or titanium forging can be used.

The forged product produced by the GATORIZING process has two distinct advantages over a cast rotor. The greater ductility and toughness attained in a forging will contribute to the reliability and durability of the small turbine engine rotors. Another advantage for forging is the greater consistency of part quality and freedom from internal defects.

Florida Research and Development Center is under contract to EPA to demonstrate the feasibility of this low cost production method for automotive turbine rotors. The general objectives of the two-phase program are as follows:

Phase I

- Design and fabricate the dies and experimentally demonstrate low-cost, mass-production manufacturing techniques for automotive turbine disks.
- Estimate the tooling and manufacturing cost for a representative automotive turbine disk for production rates of one million turbine disks per year.

Phase II

- Produce, evaluate, and deliver compressor turbine disks utilizing the recommended manufacturing process for demonstration in the EPA Baseline Gas Turbine Engine.

The current contract authorizes only the first phase, with an option to proceed with Phase II pending the results from Phase I.

The program consists of the five following major tasks:

Task 1. Basic Process Demonstration
Task 2. Process Parameter Evaluation
Task 3. Generate Design Data
Task 4. Definition of Manufacturing Process
Task 5. Manufacturing Cost Estimate

The work to date has been limited to Tasks 1 through 3, which involve the basic feasibility study and laboratory evaluation shown schematically in Figs. 84, 85 and 86. Four alloys were considered for use in the automotive turbine rotor development program: IN100, INCO 713, AF2-IDA, and NASA IIB-11. Each of these alloys has been successfully GATORIZED. P&WA has extensive experience with IN100 and therefore selected this alloy for use in the program. The basic process demonstration involves the procurement of the program material, the design and fabrication of preform forging dies, and the GATORIZING of the initial preform for baseline mechanical properties. The processing parameters for the raw material, the GATORIZING parameters, and the heat treatment were based on existing experience with IN100.

The parametric evaluation, Task 2, involves the evaluation of additional forging parameters and heat treatments. The alternate processing will be based on the results of Task 2 and will be aimed at creating the most favorable structure in the preform for subsequent finish forging and to establish a thermal process which produces mechanical properties consistent with Chrysler Corporation's design requirements. The final part of Task 2 will be the forging and evaluation of GATORIZED, integrally bladed rotors.

The design data generation, Task 3, involves the establishment of complete design curves for the short-time, long-time, and cyclic properties. It was anticipated that the optimum heat treatment for the disk portion of the wheel might not be adequate for the blades. Therefore, additional thermal cycles aimed at producing higher properties in the blade operating temperature range (1700 to 1800°F) will be evaluated.

IN100 material, vacuum-induction melted and vacuum-arc remelted from virgin metals, was provided by Allvac Metals. The material was machined and canned in stainless steel for subsequent extrusion. Cameron Iron Works extruded the material at 1066°C (1950°F) through a 180.3 mm (7.1 in) orifice, resulting in a reduction ratio of 6.8:1. The extruded material was then remachined to a 139.7 mm (5.5 in) diameter mult and recanned in stainless steel. This

PHASE I - FEASIBILITY DEMONSTRATION AND COST ANALYSIS
TASK I - BASIC PROCESS DEMONSTRATION

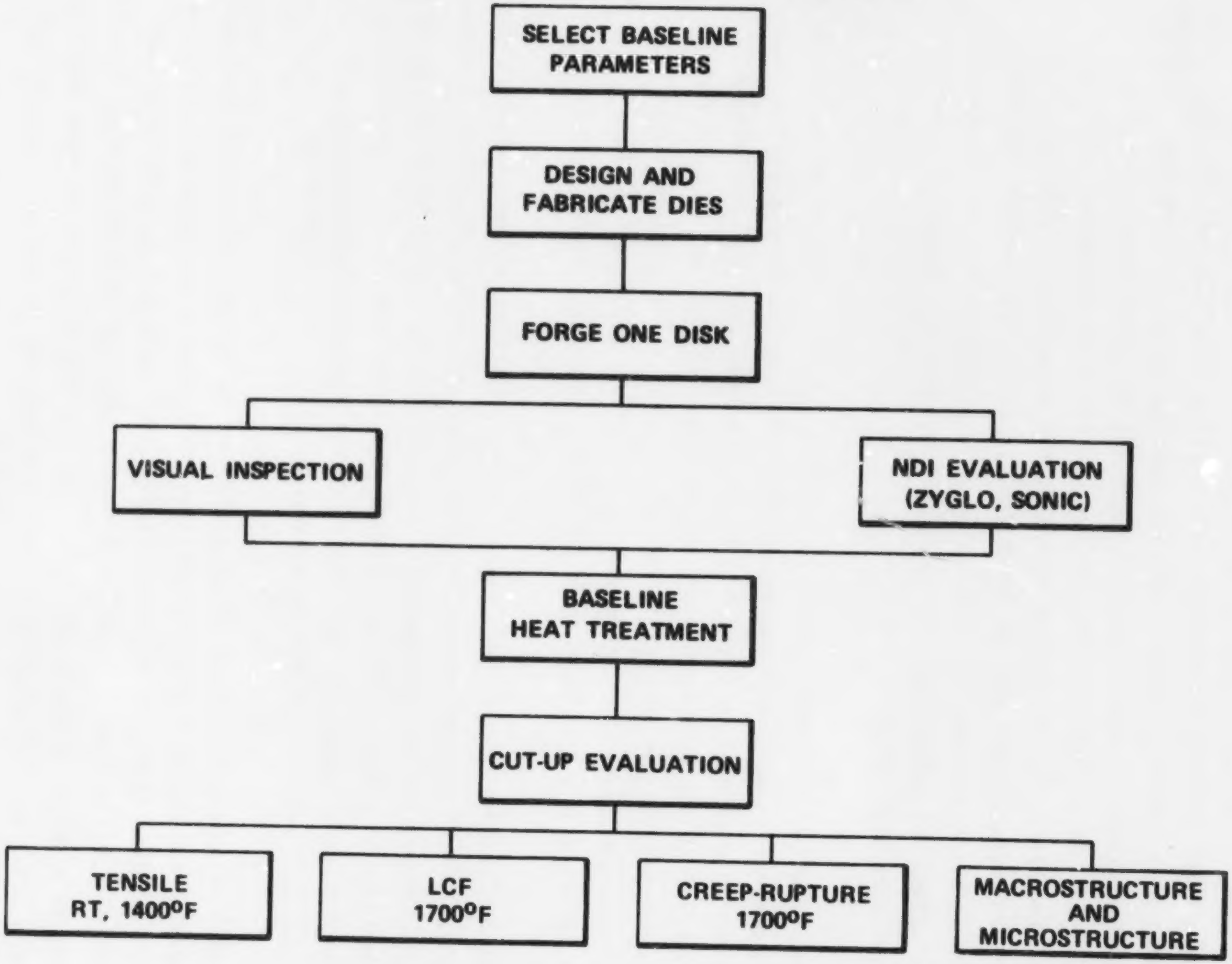

SELECT BASELINE PARAMETERS
DESIGN AND FABRICATE DIES
FORGE ONE DISK
VISUAL INSPECTION
NDI EVALUATION (ZYGLO, SONIC)
BASELINE HEAT TREATMENT
CUT-UP EVALUATION
TENSILE RT, 1400°F
LCF 1700°F
CREEP-RUPTURE 1700°F
MACROSTRUCTURE AND MICROSTRUCTURE

Figure 84

PHASE I - FEASIBILITY DEMONSTRATION AND COST ANALYSIS
TASK 2 - PROCESS PARAMETER EVALUATION

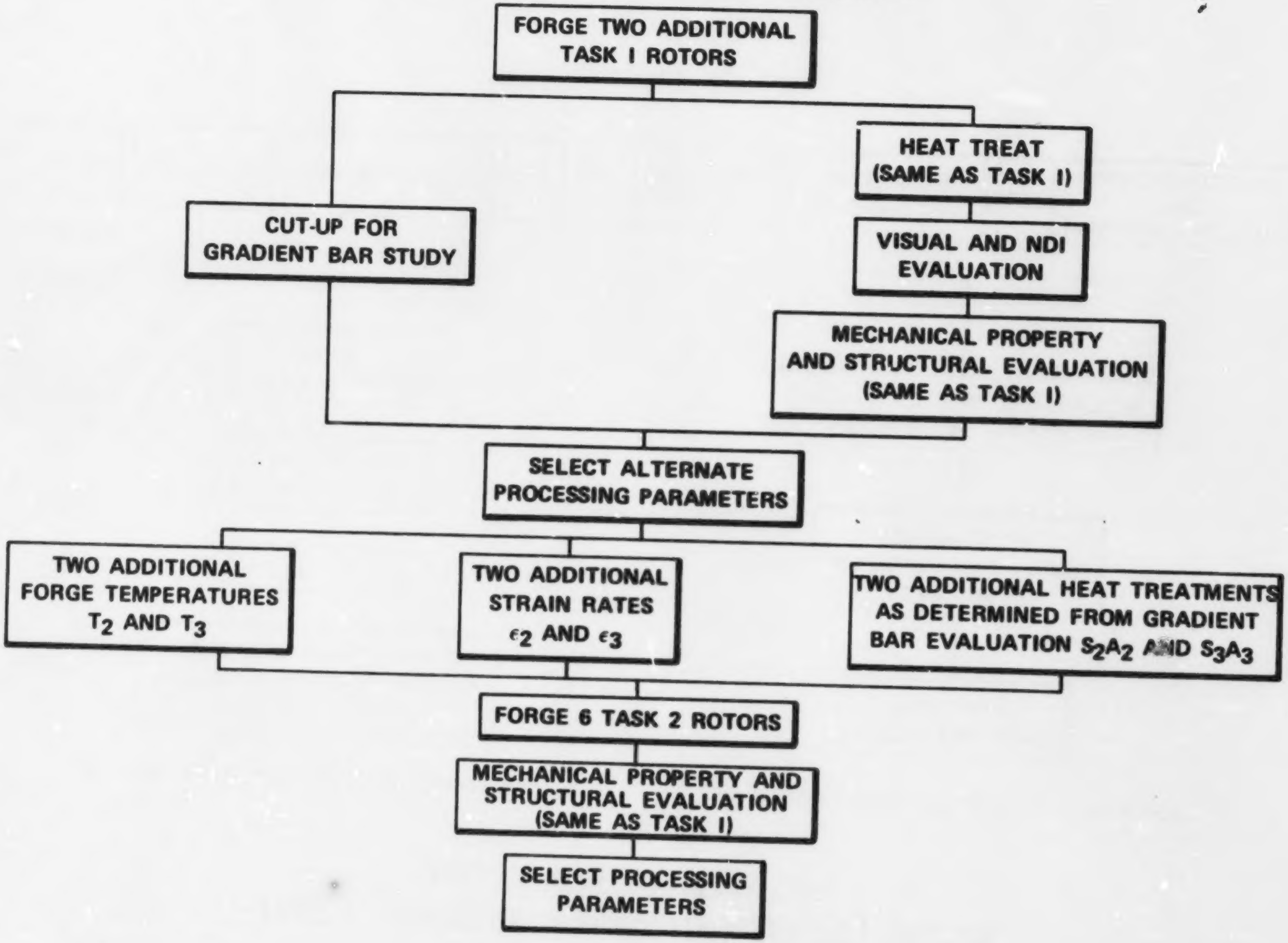

FORGE TWO ADDITIONAL TASK I ROTORS
CUT-UP FOR GRADIENT BAR STUDY
HEAT TREAT (SAME AS TASK I)
VISUAL AND NDI EVALUATION
MECHANICAL PROPERTY AND STRUCTURAL EVALUATION (SAME AS TASK I)
SELECT ALTERNATE PROCESSING PARAMETERS
TWO ADDITIONAL FORGE TEMPERATURES T_2 AND T_3
TWO ADDITIONAL STRAIN RATES ϵ_2 AND ϵ_3
TWO ADDITIONAL HEAT TREATMENTS AS DETERMINED FROM GRADIENT BAR EVALUATION S_2A_2 AND S_3A_3
FORGE 6 TASK 2 ROTORS
MECHANICAL PROPERTY AND STRUCTURAL EVALUATION (SAME AS TASK I)
SELECT PROCESSING PARAMETERS

Figure 85

PHASE I - FEASIBILITY DEMONSTRATION AND COST ANALYSIS
TASK 3 - GENERATE DESIGN DATA

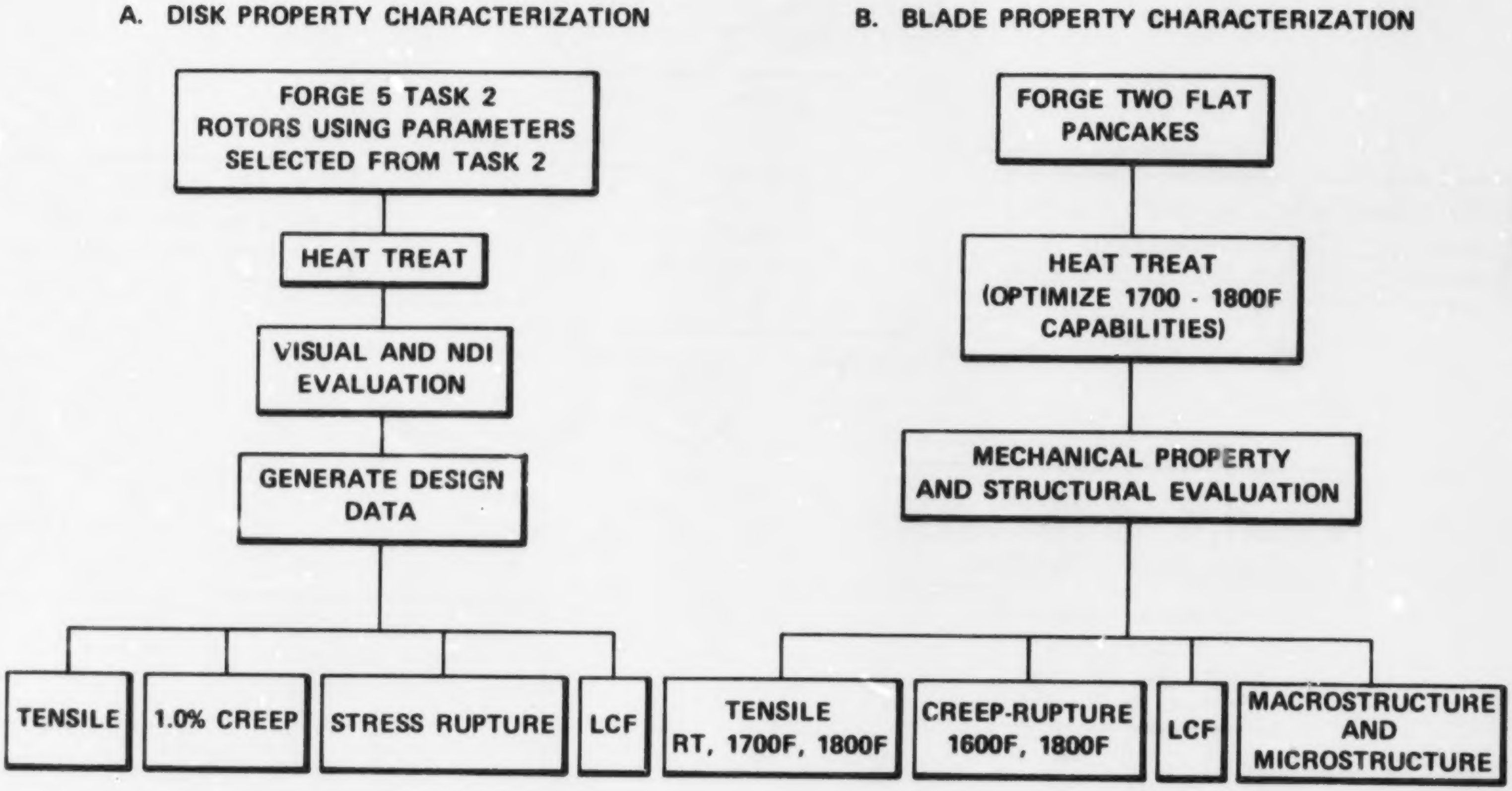

A. DISK PROPERTY CHARACTERIZATION
FORGE 5 TASK 2 ROTORS USING PARAMETERS SELECTED FROM TASK 2
HEAT TREAT
VISUAL AND NDI EVALUATION
GENERATE DESIGN DATA
TENSILE
1.0% CREEP
STRESS RUPTURE
LCF
B. BLADE PROPERTY CHARACTERIZATION
FORGE TWO FLAT PANCAKES
HEAT TREAT (OPTIMIZE 1700 - 1800F CAPABILITIES)
MECHANICAL PROPERTY AND STRUCTURAL EVALUATION
TENSILE RT, 1700F, 1800F
CREEP-RUPTURE 1600F, 1800F
LCF
MACROSTRUCTURE AND MICROSTRUCTURE

Figure 86

mult was re-extruded at RMI at 1066°C (1950°F) through a 62.23 mm (2.45 in) diameter orifice. The recanned billet and as-extruded material is shown in Fig. 87. The material as-extruded was 95 to 98% recrystallized fine grains, ASTM 11.5 to 16, with some isolated unrecrystallized areas. Standard tensile specimens were machined, and superplasticity tests were run. The following results verified that the material was in a superplastic condition.

IN100 Re-Extruded Superplasticity Test Results

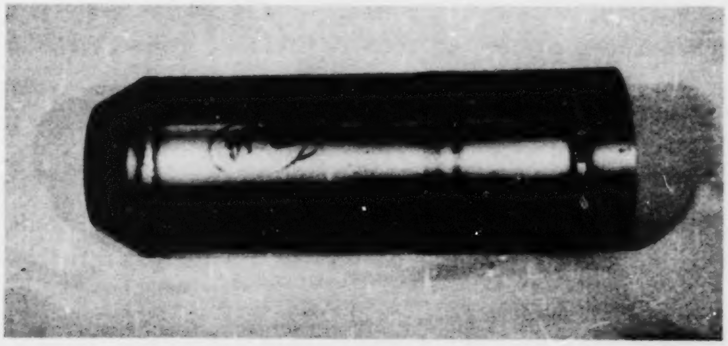
Specification No.	Temperature	Flow Stress $N/m^2 \times 10^6$	Flow Stress psi	Elongation %	Reduction of Area %
1	1079°C (1975°F)	67.7	9820	445	99.7
2	1079°C (1975°F)	58.7	8510	295	99.7

The dies used for this program will be manufactured from TZM molybdenum. This material was selected because of its excellent thermal conductivity, elevated temperature strength, and wear resistance. It is very important that temperature uniformity be achieved from the center to the edge of the die stack of the press. Experience has shown that temperature gradients are minimal in the radial direction in TZM molybdenum die stacks up to 30 inches in diameter.

Most of P&WA's experience with the GATORIZING forging process has been with this die material. Conventional machining and electrical discharge machining (EDM) techniques have been well established. The design of the dies to forge the disk will be based on past experience with the die stack design, inserts, lubricants, and metal flow characteristics.

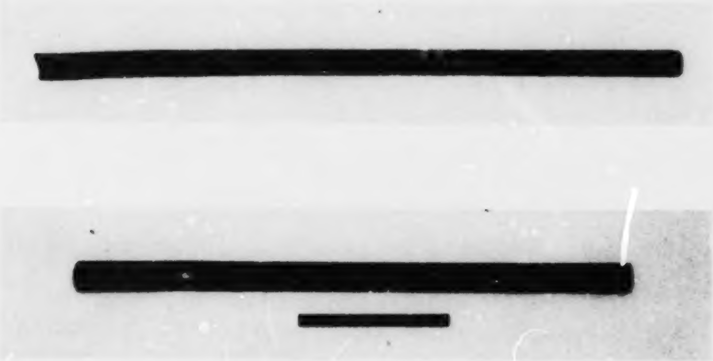
A two-step forging sequence will be used to GATORIZE the rotors. The first step produces a nonbladed oversized preform to ensure proper metal distribution for the final form. The second step reduces the disk area to final dimensions and fills the blade die insert cavities.

The preform configuration (Fig. 88) and preform dies were designed and tooling fabricated. A cross-sectional view of the preform tooling is shown in Fig. 89 and photographs of the actual tooling are shown in Fig. 90.



FAL 28671

BILLET RECANNED FOR SECOND EXTRUSION



AS-EXTRUDED MATERIAL

Fig. 87 Processing of IN100 Forging Stock

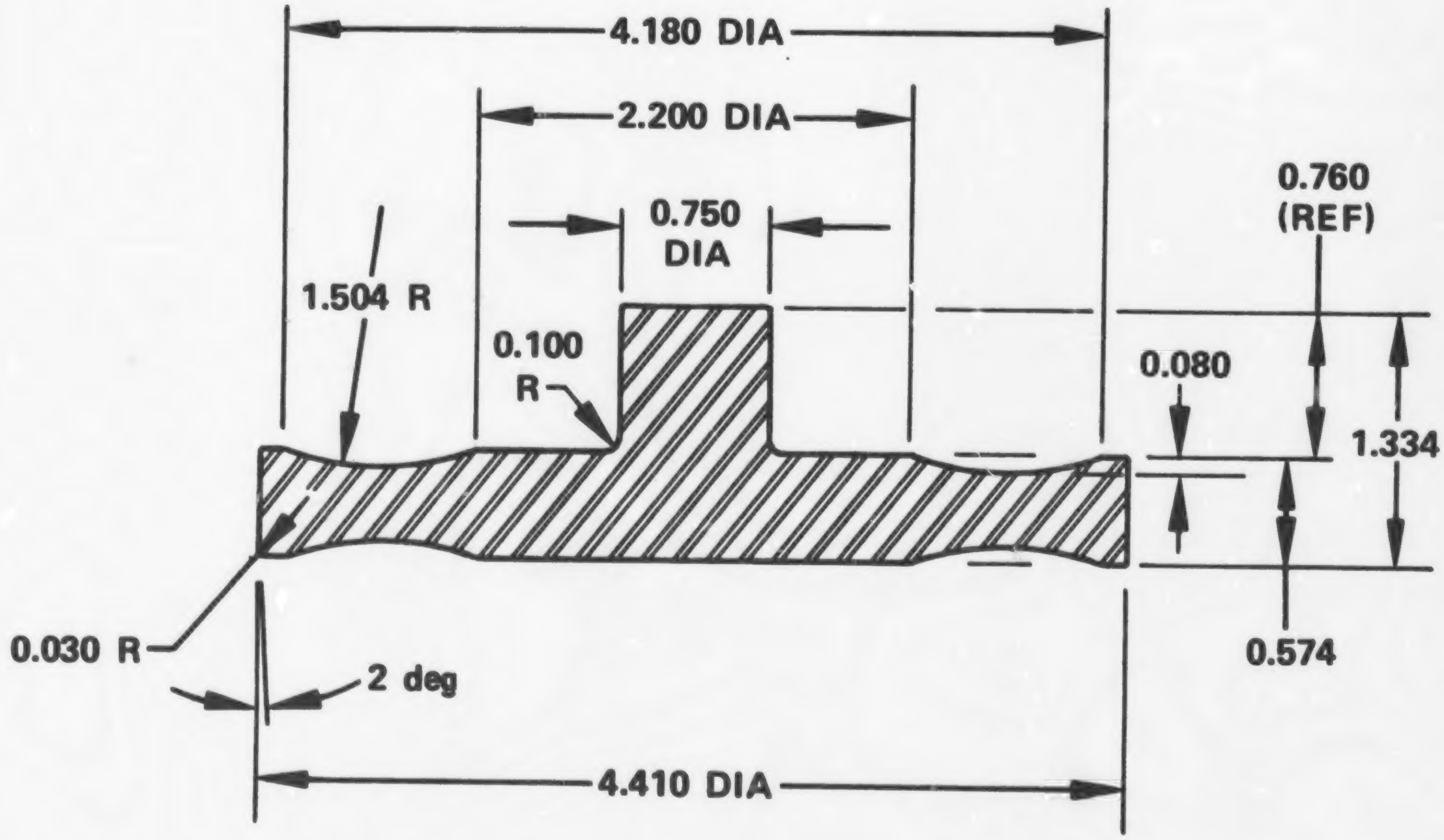

4.180 DIA
2.200 DIA
0.750 DIA
0.760 (REF)
1.504 R
0.100 R
0.080
1.334
0.030 R
2 deg
0.574
4.410 DIA

Fig. 88 Cross Section of Phase I Disk Preform

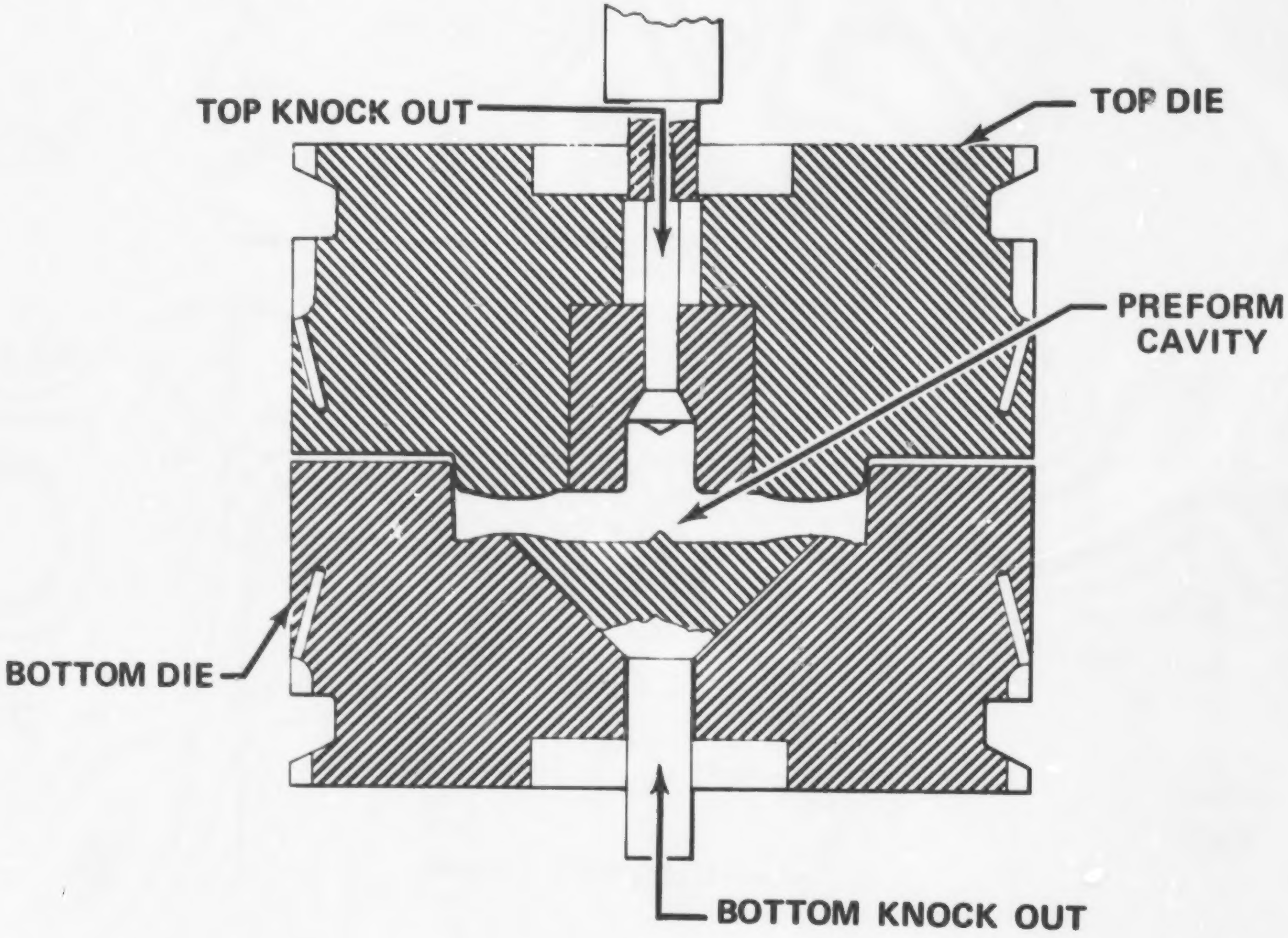

TOP KNOCK OUT
TOP DIE
PREFORM CAVITY
BOTTOM DIE
BOTTOM KNOCK OUT

Fig. 89 Tooling for Phase I – Task I Preform

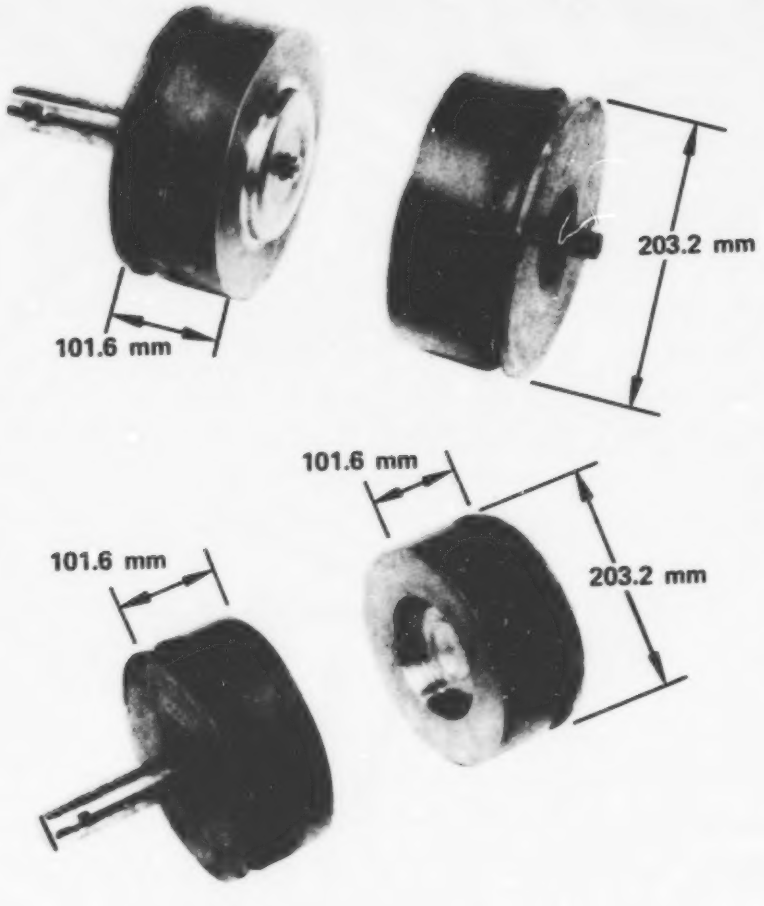

101.6 mm
203.2 mm
101.6 mm
101.6 mm
203.2 mm

Fig. 90 Finish Machined Preform Tooling

The final integrally bladed disk tooling was designed per Chrysler drawing with the exception of the pockets located in both sides of the disk rim. This final wheel configuration is shown in Fig. 91. The pockets were excluded for the initial feasibility demonstration for two reasons: (1) It was felt that the primary goal of this initial program was to demonstrate the feasibility of economically GATORIZING an integrally bladed wheel of the type used in automotive gas turbines, and (2) it is highly probable that the final wheel design can be modified, based on the improved structural uniformity and higher levels of mechanical properties, especially LCF, associated with the wrought product.

The final die design was completed in June with the exception of detailing and insert segments. Final design of the inserts were held, pending a resolution on the approach for the bladed rotor. P&WA recommended producing the bladed wheel with all 53 blades, using simple split inserts. A 5X wooden model (Fig. 92) demonstrating this concept was fabricated and reviewed. Approval was granted for the recommended approach. The final design for the dies to GATORIZE the rotor, is now complete. A cross-sectional view of the final tooling is shown in Fig. 93. Fabrication of the dies was scheduled for completion by 15 October.

Seven forging mults 44.45 mm (1.750 in) in diameter by 85.85 mm (3.38 in) high were machined from the extruded stock. The mults after being coated with a boron nitride lubricant were GATORIZED to the preform configuration. These seven forgings will be used for the Task I evaluation and portions of the Task II and Task III evaluations as shown in the following table.

Preform Forgings and Scheduled Evaluation

Forging Temperature	Program Use	
1038°C (1900°F)	Task I	Base Line Data
1038°C	Task II	Gradient Bar Study and Additional Cut-Up
1010°C (1850°F) 1070°C (1950°F) 1093°C (2000°F)	Task II	Alternate Forging Temperature Evaluation
1038°C	Task III	Blade Property Characterization

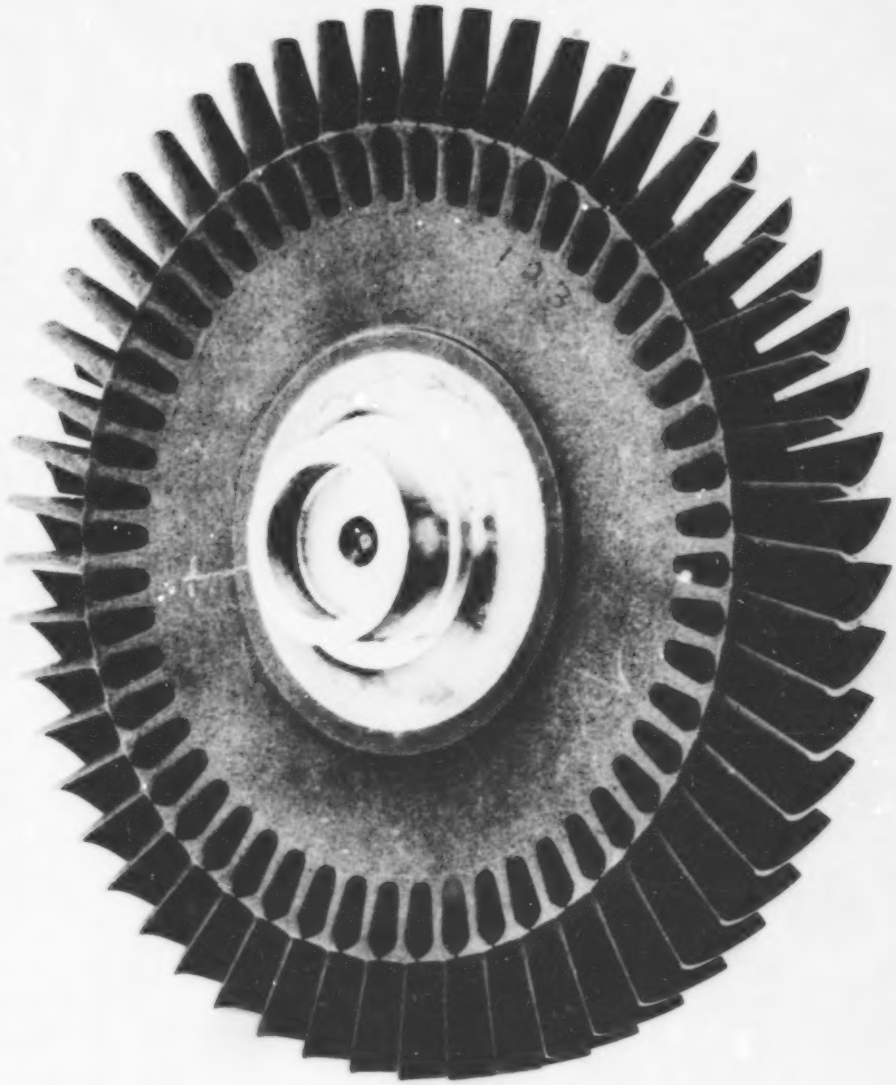


Fig. 91 Automotive Gas Generator Turbine Rotor

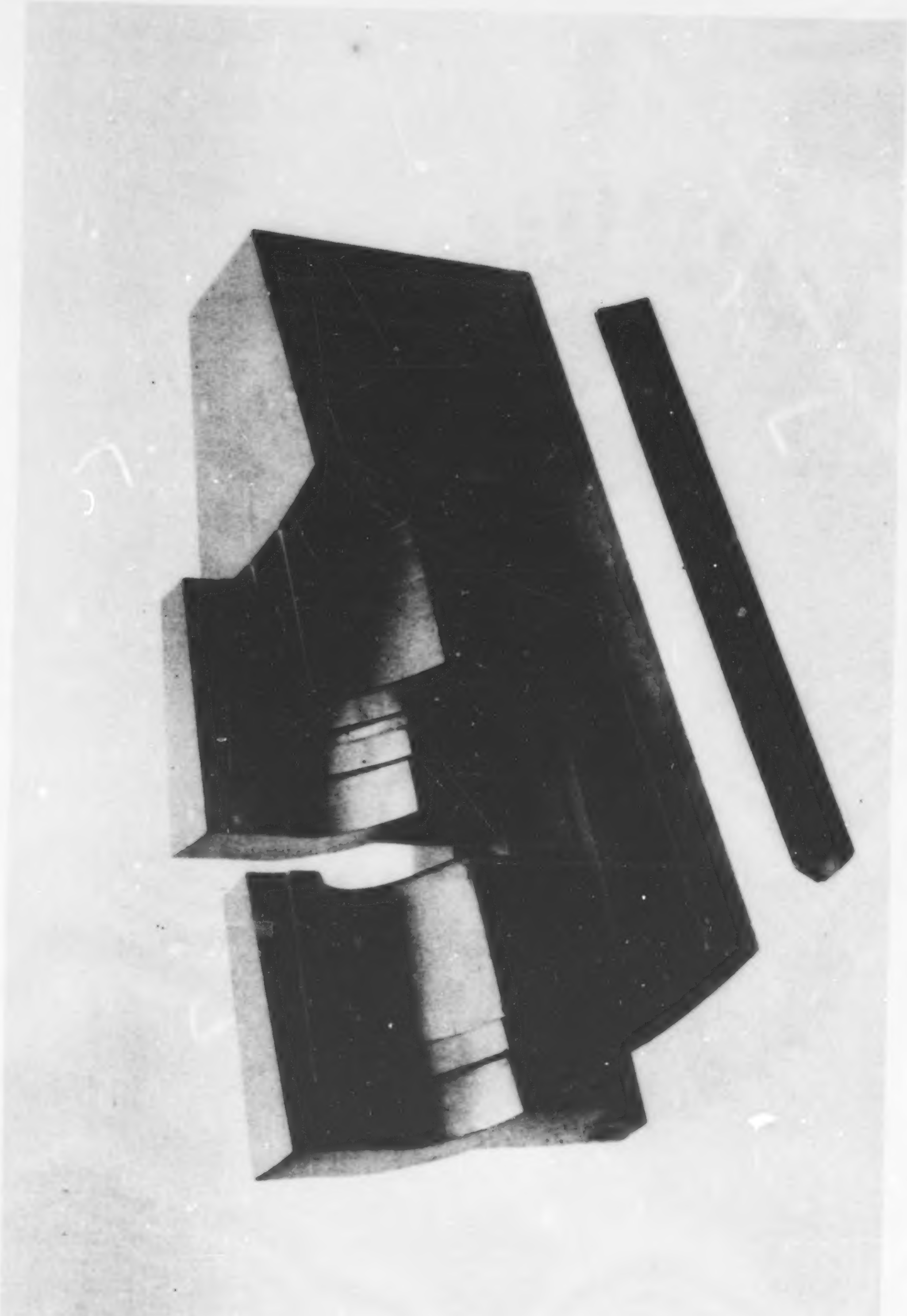


Fig. 92 Blade Insert Concept Used for Finish Die Design

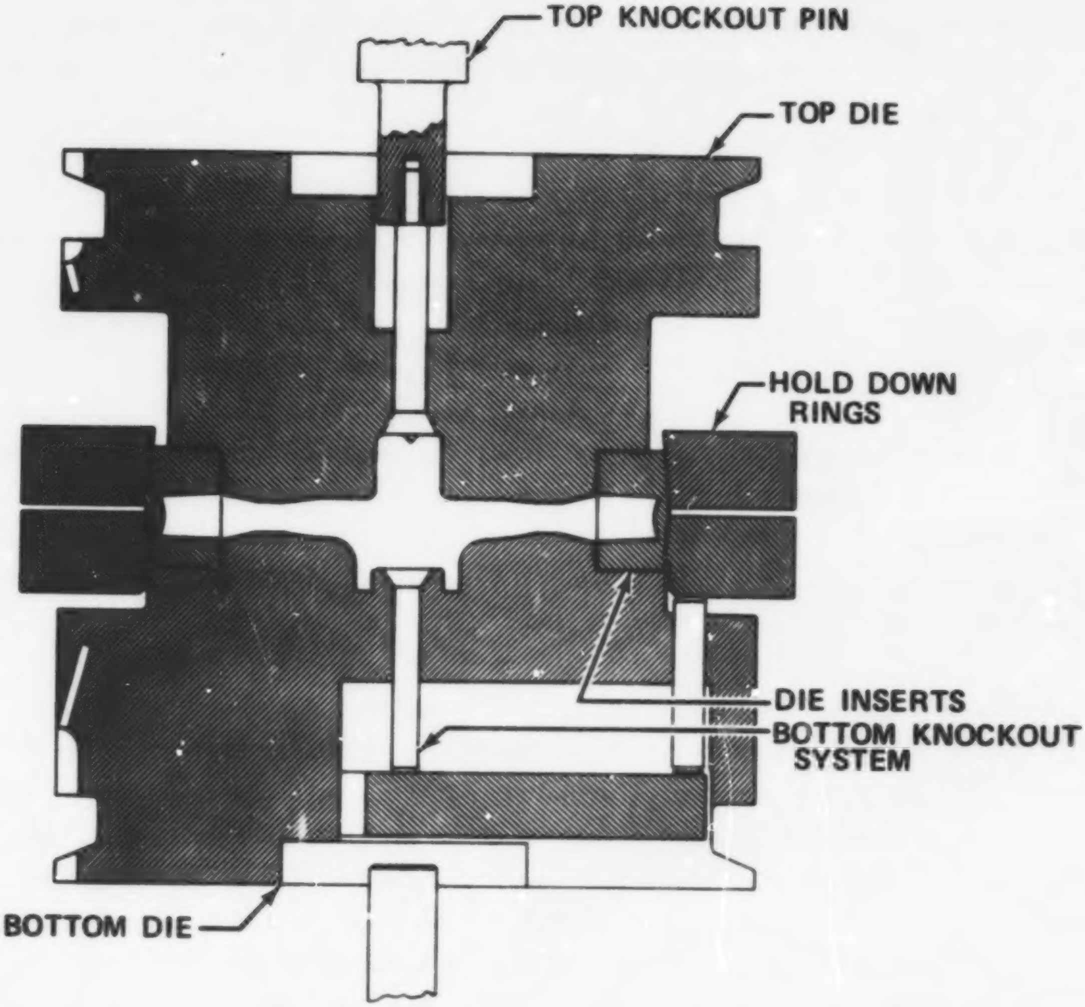

TOP KNOCKOUT PIN
TOP DIE
HOLD DOWN RINGS
DIE INSERTS
BOTTOM KNOCKOUT SYSTEM
BOTTOM DIE

Fig. 93 Tool for Phase I – Task II Bladed Rotor

The 1038°C (1900°F) forging temperature used for the first three preforms was based on current experience with wrought IN100. These preforms will be heat treated and cut-up for the initial Tasks I and II structural and mechanical property evaluation as shown in Fig. 94. A typical forging mult, preform forging and resulting microstructure is shown in Fig. 95.

It was anticipated that the superplasticity of an extruded ingot would be significantly less than that of a similarly processed powder metallurgy product. Therefore the forging temperature evaluation and the use of a preform was included in the program to ensure attaining optimum forgability. As noted previously, the maximum elongation measured on the extruded ingot was 445%. This compares with a value of 1400% normally achieved on extruded powder. Based on the microstructural evaluation on the first three preforms forged at 1038°C, the additional forging temperatures noted in the above table were selected. The aim being to produce the finest, fully recrystallized structure attainable for subsequent finish forging. These forgings are currently being cut-up for structural and mechanical property evaluation.

The one additional preform forging is being used for the initial Task III blade property characterization. The purpose of this evaluation is to establish a heat treatment (primarily modified solution temperature) to produce a coarser grained structure which would exhibit mechanical properties commensurate with blade operating temperatures. At this point in the program it is not known whether or not preferential solutioning of the blades will be required. This will be determined by the results of the Task I and II mechanical property evaluation and Chrysler's final design requirements.

Points Clarified during Question/Answer Period

- Mass production cost estimates have not been made yet. Since normal production levels for P&WA are about 400-500 units per year, automotive production levels (100,000 to 1 million per year) will require special consideration of automation and high-volume production techniques.

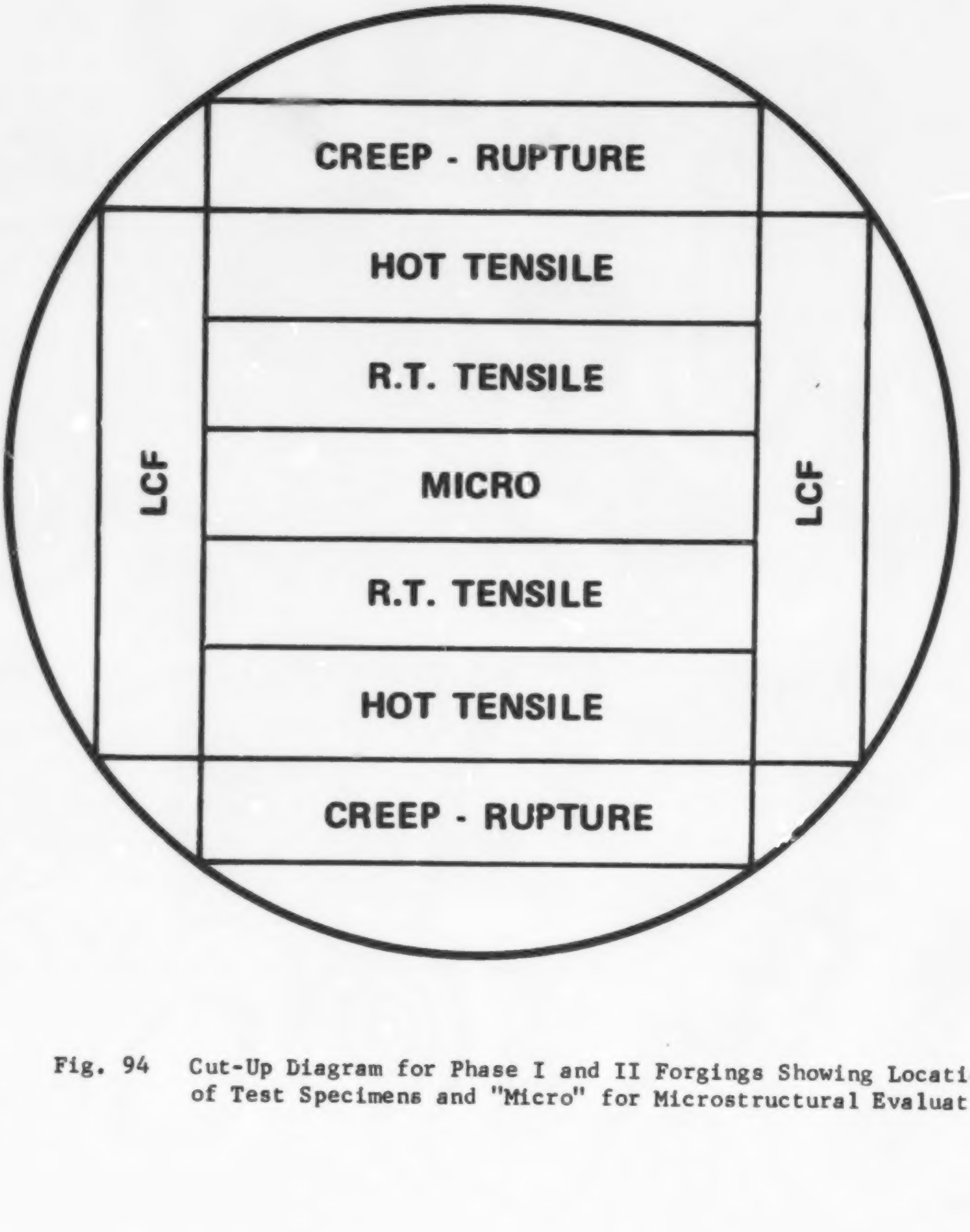
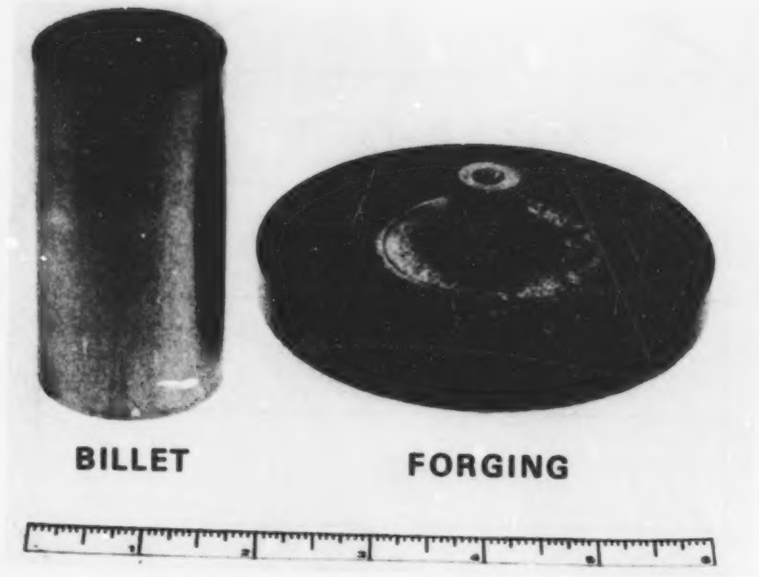
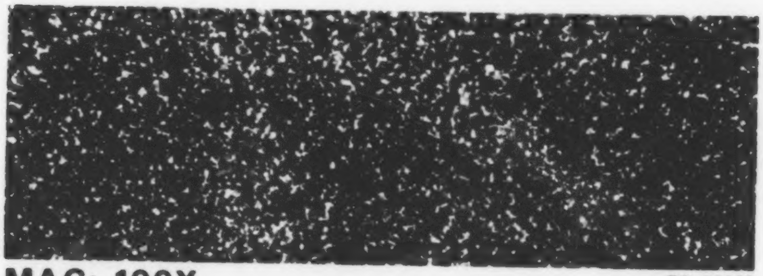

CREEP - RUPTURE
HOT TENSILE
R.T. TENSILE
MICRO
R.T. TENSILE
HOT TENSILE
CREEP - RUPTURE
LCF
LCF

Fig. 94 Cut-Up Diagram for Phase I and II Forgings Showing Location of Test Specimens and "Micro" for Microstructural Evaluation


BILLET
FORGING
1
2
3
4
5
6

FAE 131443



MAG: 100X

FD 74446

TYPICAL MICROSTRUCTURE

Fig. 95 Task I Preform

- Estimated total time to make one wheel is 3 - 5 minutes.
- Die insert and die life at the high production rates will have an important influence on cost. Special lubricants, coatings, cast ceramic inserts are being considered in this regard.
- Definition of the process and production cost estimates are scheduled for completion in January 1974. Results should be available for the next coordination meeting.
- Tool wear and die life are still major questions.
- Although no formal presentation was made (no current EPA contract) it was mentioned that a competitive low cost turbine wheel manufacturing process is the rubber pattern casting technique of AiResearch Casting Division. This is another very promising low cost approach and is well along in development.

H. Owens-Illinois Oxide Recuperator Development, by K. Kormanyos, Project Manager, Owens-Illinois, Toledo, Ohio

The purpose of this program is to examine the potential of a low expansion, oxide, compact recuperator for application in an automotive gas turbine system. Initially, the scope of work included four tasks; but recent modifications have extended the scope to include the following six tasks:

1. Parametric Design Analysis
2. Fabrication Feasibility
3. Conceptual Design Analysis for Specific Engine Requirements
4. Fabrication and Testing of Scaled Down Cores Under Approximate Engine Conditions
5. Seal Development (Problems associated with installations of low expansion oxide in a metal housing)
6. Recuperator Cost Analysis

The parametric design analysis and manufacturing feasibility tasks were completed in their entirety. Work associated with the design for specific engine requirements was revised by the modification and essentially has been completed at this time. The conceptual geometrics considered are shown in Fig. 96. The relative sizes and calculated results are shown in Figs. 97 and 98 respectively. The single pass crossflow was selected as the most promising concept.

Additional core sizing curves and formulas were developed for the single pass crossflow geometry based on modified mass flow rates and heat exchanger requirements, supplied by Chrysler, to represent a no leakage case. For comparison the core was sized: with associated regenerator leakage, without leakage, and with reduced effectiveness due to realized increase in power output for no leakage. The results are shown in Fig. 99.

Scaled-down test cores are being fabricated and design of test equipment is underway. Testing will include:

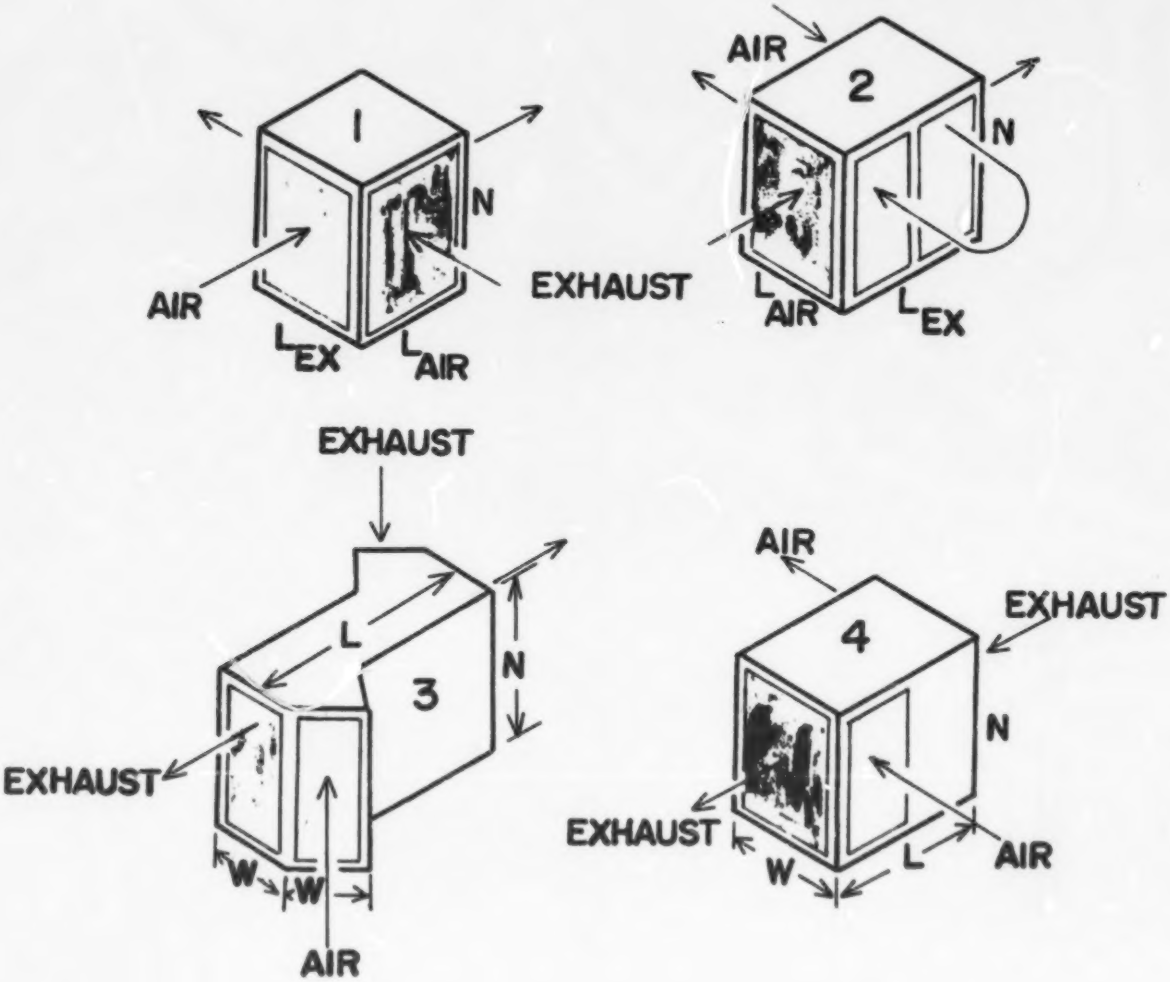
- Core leakage characterization
- Core burst test
- Thermal shock test

The test core is shown in Fig. 100. It measures 5 in. on a side. The hydraulic diameter is approximately 0.025 in..

The cost analysis task has been retained and is scheduled to begin after the testing program is in operation.

Points Clarified during Question/Answer Period

- Ceramic material, C-126, is being used initially with a maximum temperature capability of about 1500°F. Other possible materials are also being considered.
- No information about the metal-ceramic sealing or fastening problem was released as yet, since this is Task 5.
- It was observed that the single pass crossflow configuration is a very inefficient arrangement on an effectiveness to mass flow ratio basis compared to the other configurations.


1
AIR
EXHAUST
N
L_{EX}
L_{AIR}
AIR
2
N
L_{AIR}
L_{EX}
EXHAUST
3
L
N
EXHAUST
W
W
AIR
AIR
4
EXHAUST
N
EXHAUST
W
L
AIR

Single-Pass Cross Flow

Two-Pass Cross Counterflow

Externally Headered Counterflow

Internally Headered Counterflow

Fig. 96 Conceptual Geometries

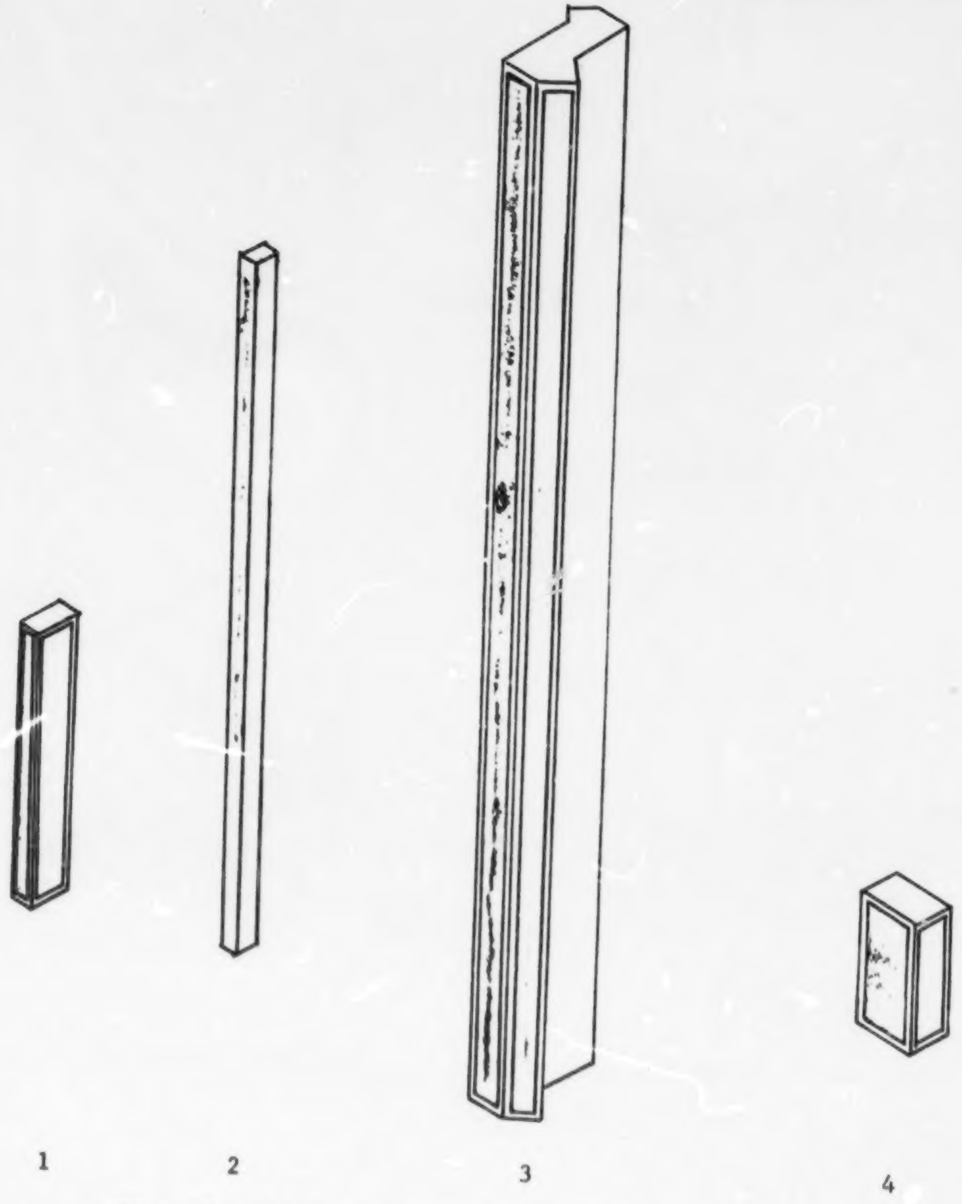


Fig. 97 Relative Sizes for Equal Performance

Single Pass Crossflow

L_{AIR} = 6.04 IN.
L_{EX} = 4.12 IN.
N = 38.2 IN.
V_T = 951 IN.^{3}
W_T = 24.7 LB.

Two Pass Cross-counterflow

L_{AIR} = 2.46 IN.
L_{EX} = 3.35 IN.
N = 105 IN.
V_T = 865 IN.^{3}
W_T = 24.4 LB.

Externally headered Counterflow

W = 6 IN.
L = 14.76 IN.
N = 144 IN.
V_T = 17937 IN.^{3}
W_T = 456 LB.

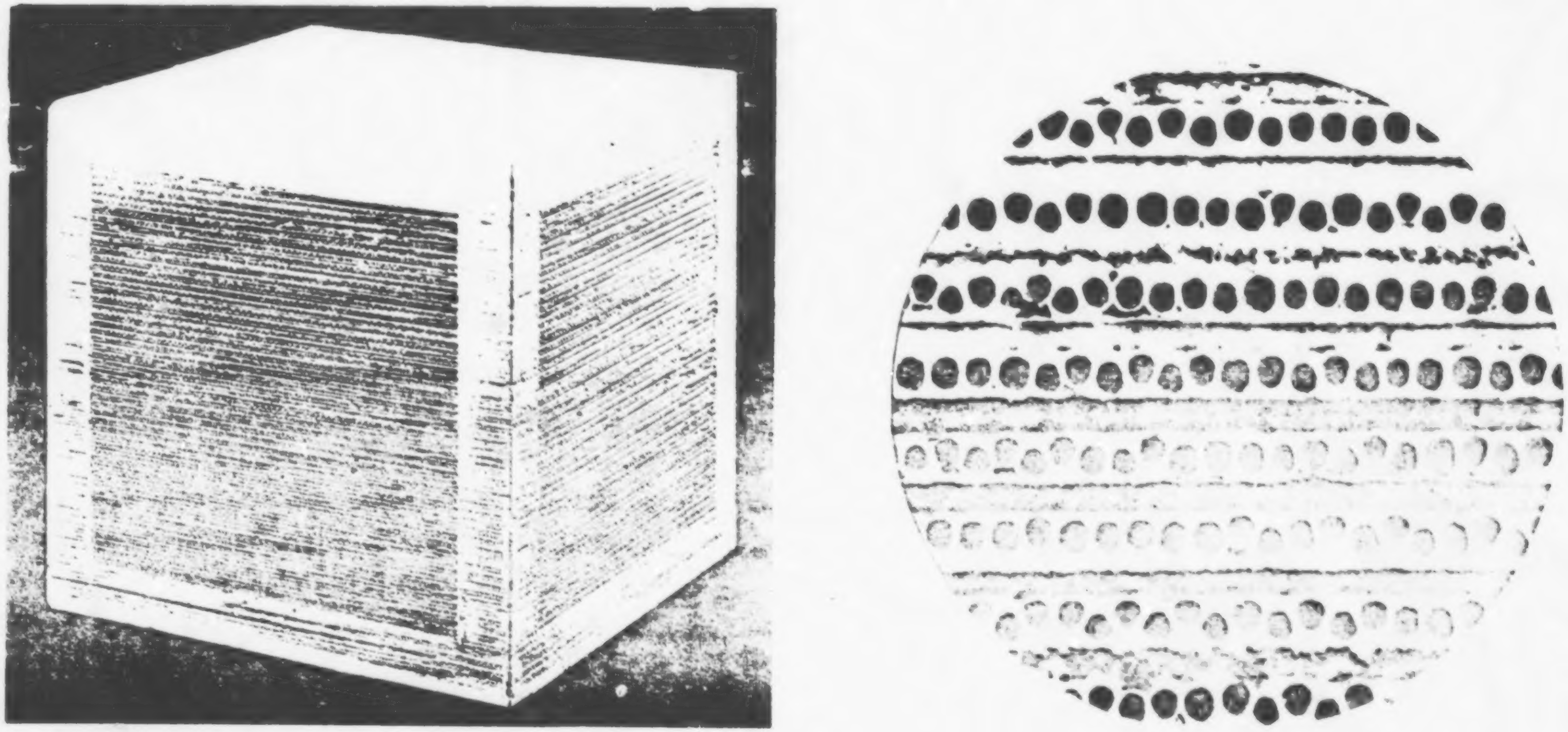
Internally Headered Counterflow

W = 8.86 IN.
L = 5.52 IN.
N = 17.72 IN.
V_T = 867 IN.^{3}
W_T = 16.37 LB.

Fig. 98 Calculated Sizing for Conceptual Core Geometries

	REQ'D. EFF.	L_{AIR}	L_{EX}	N	v_T	w_T
WITH INTRINSIC LEAKAGE	.85	6.04	4.12	38.2	951	24.7
WITHOUT LEAKAGE	.85	6.25	4.61	31.33	903	23.38
MODIFIED EFF. WITHOUT LEAKAGE	.802	4.66	3.49	33.9	551	14.48

Fig. 99 Comparison Results Single Pass Crossflow Cases



TEST CROSSFLOW CORE

TYPICAL FACE PHOTO

Fig. 100 Test Core

- The extra material needed for the external headering arrangement accounts for the 20:1 disadvantage in total volume.
- It was stated that for the same effectiveness (85%) and pressure drop (7.5%), a metal recuperator would require only about 2 cu. in. per HP (order of magnitude).
- It was suggested that the ceramic recuperator might be considered as a crushable material on the front of the vehicle for safety reasons.
- Accurate figures for a realistic comparison of the rotating regenerator and the oxide recuperator, on the basis of weight, size, and effectiveness, were not available.
- The principle heat exchanger program of EPA is limited to replacing the metallic rotary regenerator on the Chrysler Baseline Engine with a ceramic regenerator since it is believed to have an ultimate potential for higher effectiveness at part load, higher temperatures, and lower cost. Some information on seal experience with the metallic core was presented above by Chrysler. Although no additional information on these seals is expected, it is anticipated that the results of the seal work on ceramic cores will be fully reported. The work on the oxide recuperator is a technology program only and, although it is using some of the Baseline Engine design parameters, there are no plans at present to integrate this type heat exchanger into the Baseline Engine Program.
- A status report on the health hazard of Nickel Oxide seal materials is included as Appendix G of this report. It is not a serious, immediate hazard but it does warrant care, particularly in the manufacturing operation.

IV. RANKINE ENGINES

A. Rankine System Development Overview, by George M. Thur, Chief, Power Systems Branch, AAPSD, EPA

The goals of the program are to meet 1/2 of the 1976 Emission Standards, improve the fuel economy over conventional, pre-controlled vehicles by 50%, have the same performance, and still fit into a full size car.

A number of significant problems were identified at the beginning of the program:

- emissions
- reduction in size and weight of system, particulary the burner-boiler
- control system complexity
- freezing of water-base fluid
- organic fluid degradation with time and temperature
- lubrication, particularly in reciprocating systems
- valving response and complexity
- cost

The emissions problem is considered solved based on test results to date. Considerable progress has been made on the other problems, as is apparent from the contractor summaries presented below.

All of the four contractors are in the pre-prototype development stage and expect to demonstrate emission and fuel economy goals by the end of 1973 (Fig. 101). At that time, one of the four approaches as listed below will be selected to do the prototype development and vehicle demonstration by 1975. The four current contractors and their respective approaches are:

- Aerojet Liquid Rocket Company: organic-turbine
- Lear Motors Corporation: steam-turbine
- Thermo-Electron Corporation: organic-reciprocating
- Scientific Energy Systems Corporation: steam-reciprocating

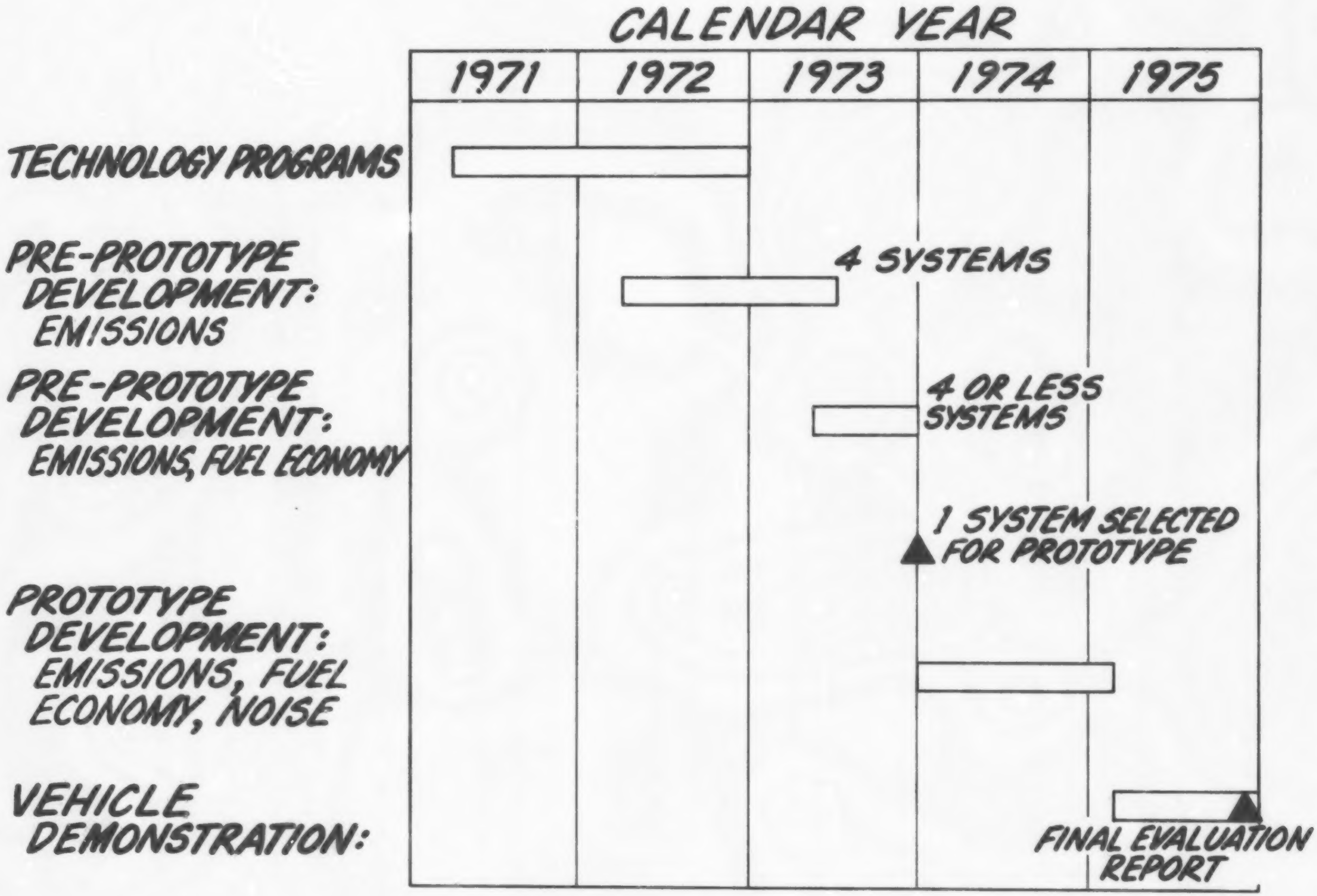


Fig. 101 Rankine System Schedule

Very little technology development work has been directed to steam automobiles over the last 40 years, so there was a lot of fundamental work to be done on each system component. A significant effort was devoted to fuel economy improvement by each of the contractors over the last 6 to 8 months. The specific approaches and anticipated gains are shown in Fig. 102. It is believed that these efforts are beginning to pay off and that the 1975 goals will be achieved. The current status and projected achievements are shown in Fig. 102.

B. Critical Components for Automotive Rankine Systems, by Mr. Ove Platell, Project Manager, Steam Power Systems, Aerospace Division, Saab Scania, Sweden

The steam power project was initiated on a study basis at Saab-Scania about 10 years ago. At that time low pollution was not considered. Actual development started in 1968 on a very limited scale - essentially a theoretical study. This identified the critical problems.

When air pollution became a world-wide problem, the arguments for Rankine systems received even more emphasis. At that time experimental hardware was built to verify a number of new ideas and test new philosophies for heat transfer. Practically all of the experimental work verified the new ideas and gave credibility to the projected performance.

Tests with different self-lubricating materials in the piston, piston rings and cylinders indicate that the problem of lubricating the steam engine can be solved without liquid lubricant additives.

A basic philosophy throughout the system is to use extremely small hydraulic diameters for all heat transfer requirements. Special attention is given to keeping the narrow slots clean. Use of water of course makes it necessary to solve the freezing problem. This is accomplished with an auxiliary engine and the condenser buffer.

The extremely small hydraulic diameters used in the steam generator give high

ITEM	IMPROVEMENT THROUGH	ASSUMPTIONS	FUEL ECONOMY GAIN
CARBURETION	• ATOMIZATION • MIXING • WARM-UP	SUCCESSFUL LEAN COLD STARTS	FDC(@50°F) 15% FDC(@0°F) 30%
FUEL INJECTION	• NO INTAKE HEAT MIXING • NO DECEL. FUEL	LOW EMISSIONS MAINTAINED	FDC 15% CDC 15%
IGNITION	• SPARK ENERGY • SPARK DURATION	COMPLETE BURNING OF LEAN MIXTURES	FDC 5% CDC 3%
STRATIFICATION	• NO THROTTLING • COMP. RATIO • LEAN MIXTURE	LOW EMISSIONS MAINTAINED	FDC 30% CDC 20%
TRANSMISSION MODIFICATIONS	• TORQUE CONVERTER LOCK-UP	LOCK-UP IN 2ND GEAR. GOOD SHIFT QUALITY	FDC 10% CDC 8%
INFINITELY VARIABLE TRANSMISSION	• OPTIMUM ENGINE OPERATION • EFFICIENCY	TRACTION DEVICE HIGH EFFICIENCY AT LOW LOAD AND SPEED	FDC > 20% CDC 20%

Fig. 102 Projected Fuel Economy Gains for Rankine System

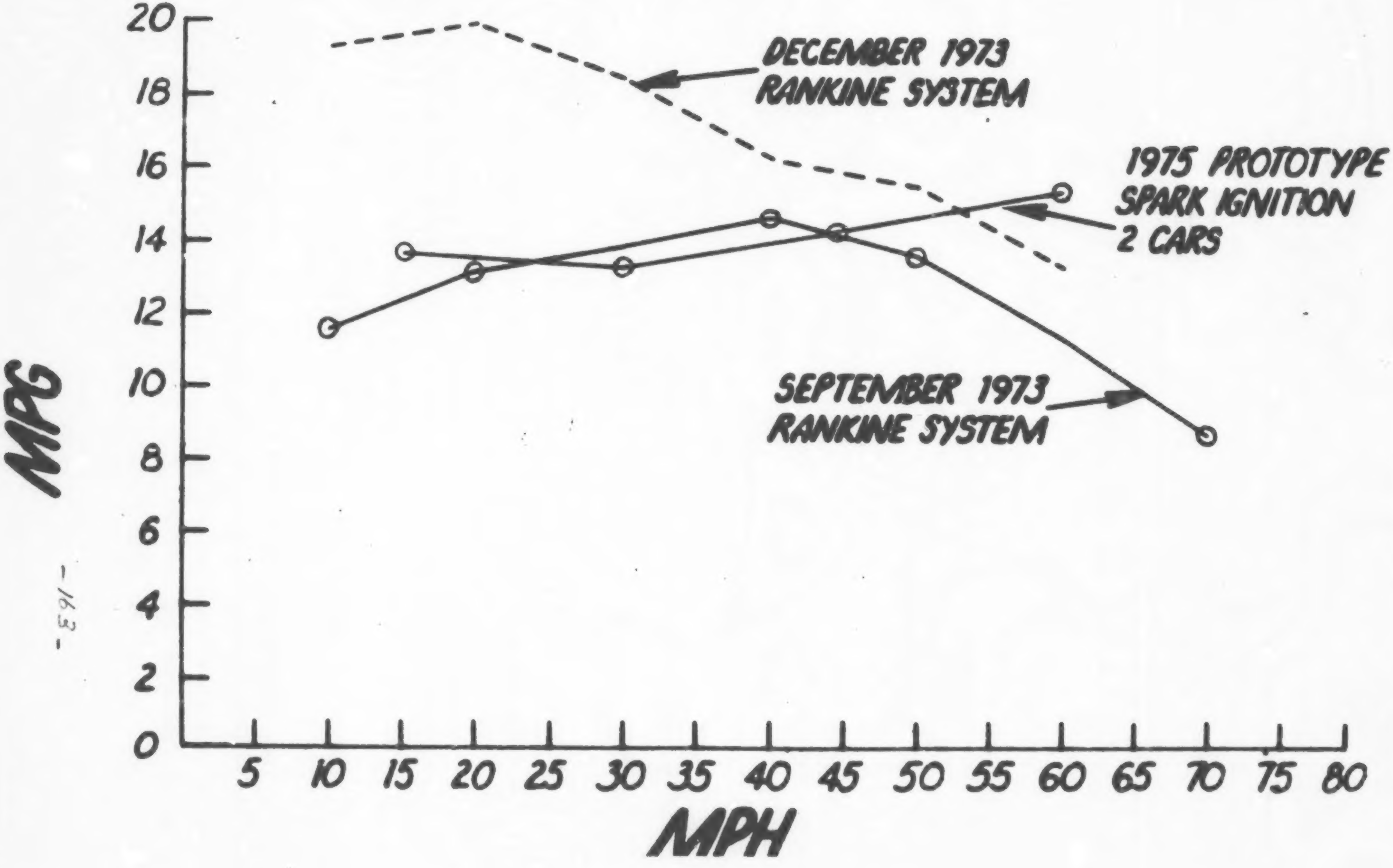


Fig. 103 Steady-State Fuel Economy - 4500-lb Vehicle, Clayton Dynamometer

compactness. To reduce weight and pressure drop on the steam side, a parallel arrangement of a great number of very thin tubes is applied. The tubes are in good thermal contact with each other to give stable operation and to avoid the problem of burn out.

The air cooled condenser will have an intolerable size if it is designed for peak power. However, when a condenser buffer is connected to the condenser, this unit only has to be designed for the mean power. This makes the cooling problem quite realistic to solve.

Then with extremely small hydraulic diameters, it is possible to obtain a reasonable condenser size. It is important that both the air and the steam side have small hydraulic diameters.

By a special V-arrangement in the condenser the pressure drop for the cooling air is reduced to the extent that enough air flow can pass through the system without bulky ducting. Special care, however, has to be taken for low pressure drop in the ducts.

The characteristic features of the projected engine are:

- Working Medium - water, hermetically sealed
- Motor - 9 cyl. wobbleplate piston engine directly connected to differential (no transmission)
- Steam Generator - multi-micro tubes in parallel arrangement
- Condenser Buffer - for peak loads
- Aircooled Condenser - extremely small hydraulic diameters
- Auxiliary System - driven by a separate constant speed steam engine
- Thermal Insulation - no freezing

Figure 104 is a block diagram of the system, and Fig. 105 summarizes the projected performance. Figure 106 shows how the system would fit in a car. The main engine, the steam generator, and the condenser are shown in Figs. 107, 108, and 109, respectively.

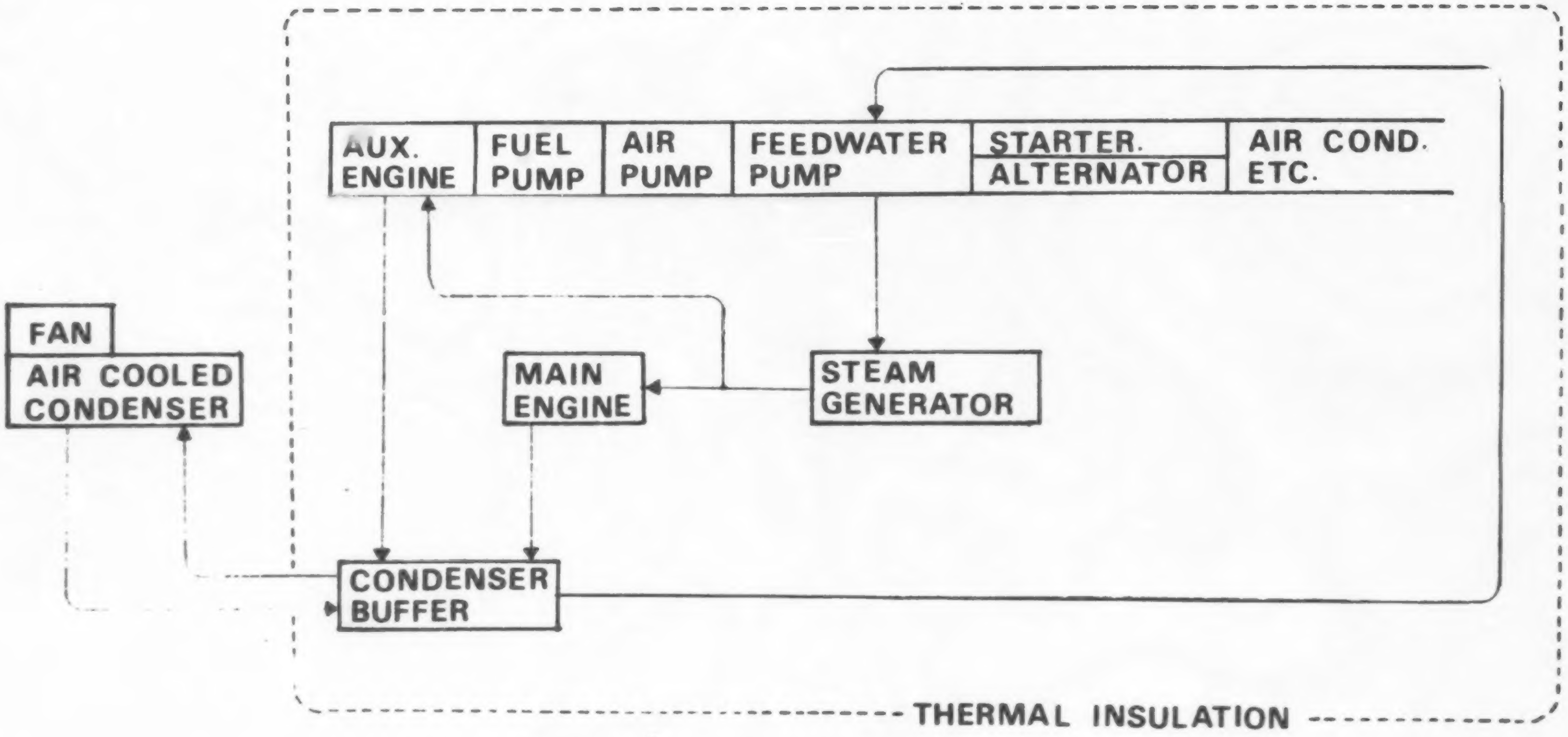

FAN
AIR COOLED CONDENSER
AUX. ENGINE
FUEL PUMP
AIR PUMP
FEEDWATER PUMP
STARTER.
ALTERNATOR
AIR COND. ETC.
MAIN ENGINE
STEAM GENERATOR
CONDENSER BUFFER
THERMAL INSULATION

Fig. 104 Block Diagram of System

STEAM DATA		100 atm; 350-450 °C
MAX MOMENTARY POWER		250 hp
MAX CONTINUOUS POWER SET BY:		
	MOTOR	250 hp
	STEAM GENERATOR	160 hp
	CONDENSER	160 hp

TOTAL WEIGHT — lower than conv. 100 hp engine.

SPACE-REQUIREMENT — same as " " "

FUEL-CONSUMPTION — lower than " " " in FDC*

UNWANTED EMISSION — highest potential for low pollution.

NOISE & VIBRATION — almost non-existing.

*Federal Driving Cycle

Fig. 105 Performance Data

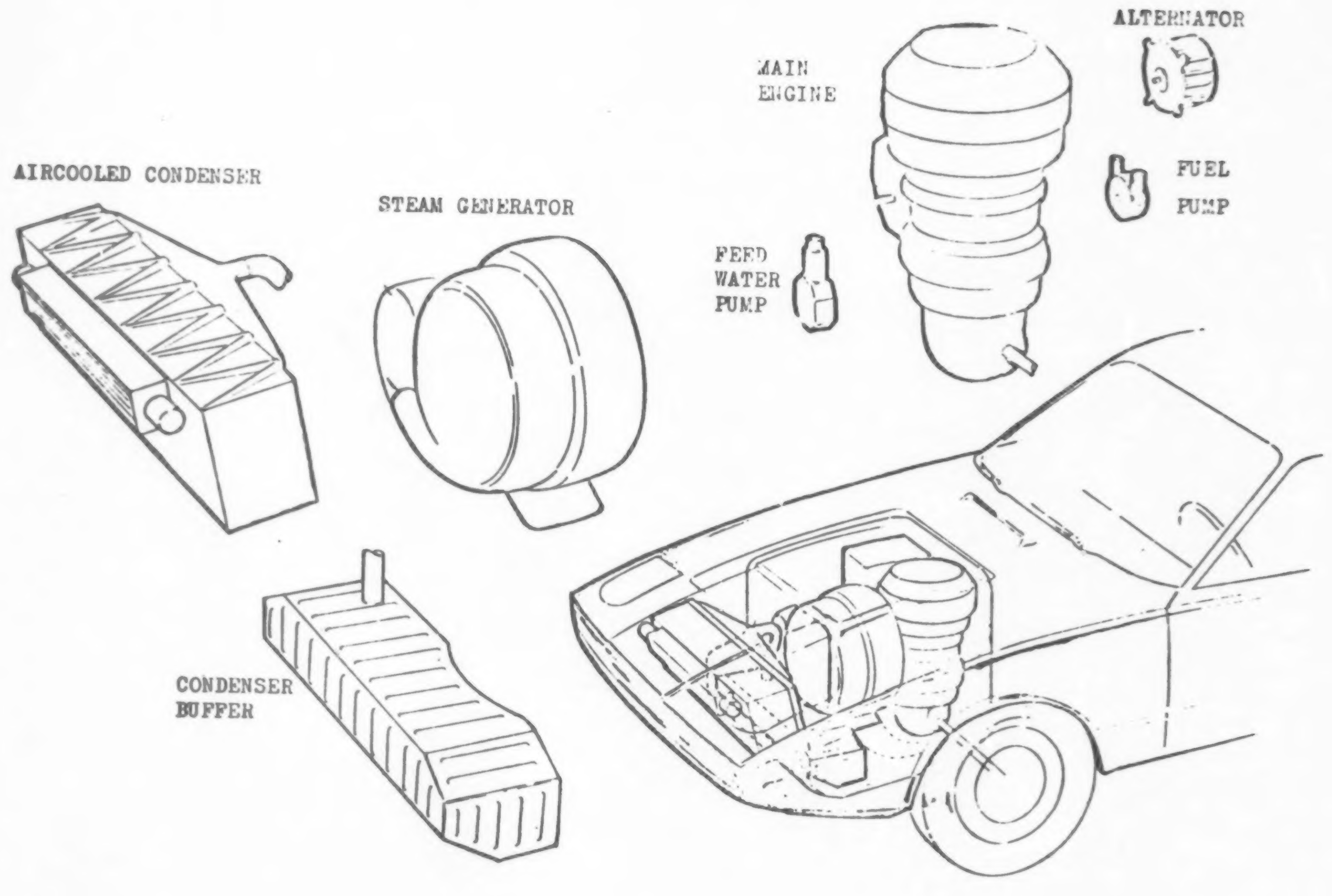

ALTERNATOR
MAIN ENGINE
AIRCOOLED CONDENSER
STEAM GENERATOR
FUEL PUMP
FEED WATER PUMP
CONDENSER BUFFER

Fig. 106 Installation in Car

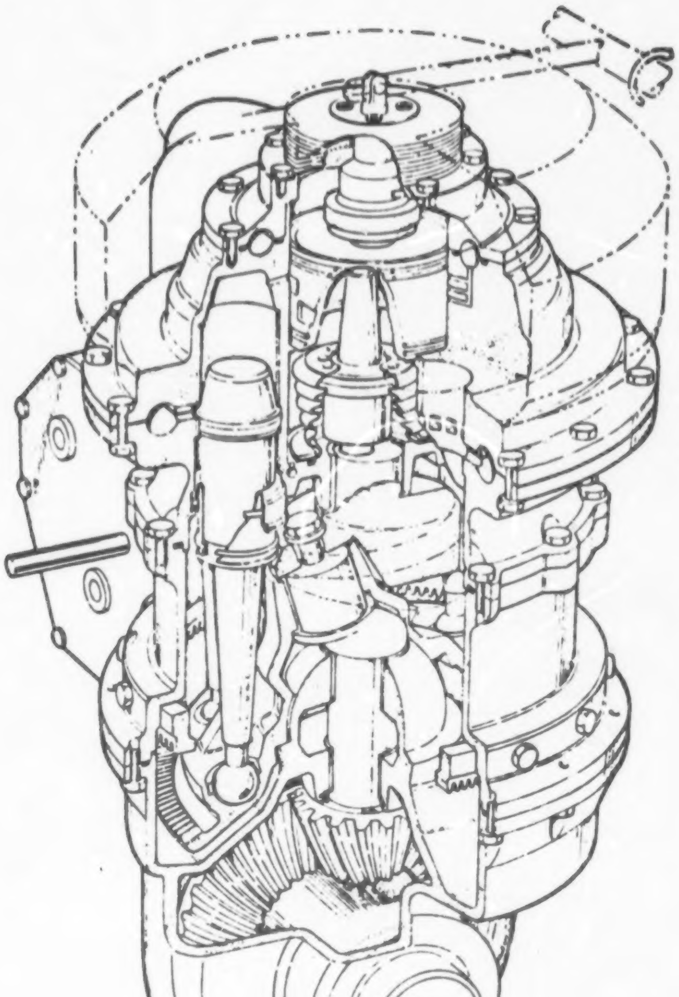


Fig. 107 Main Engine

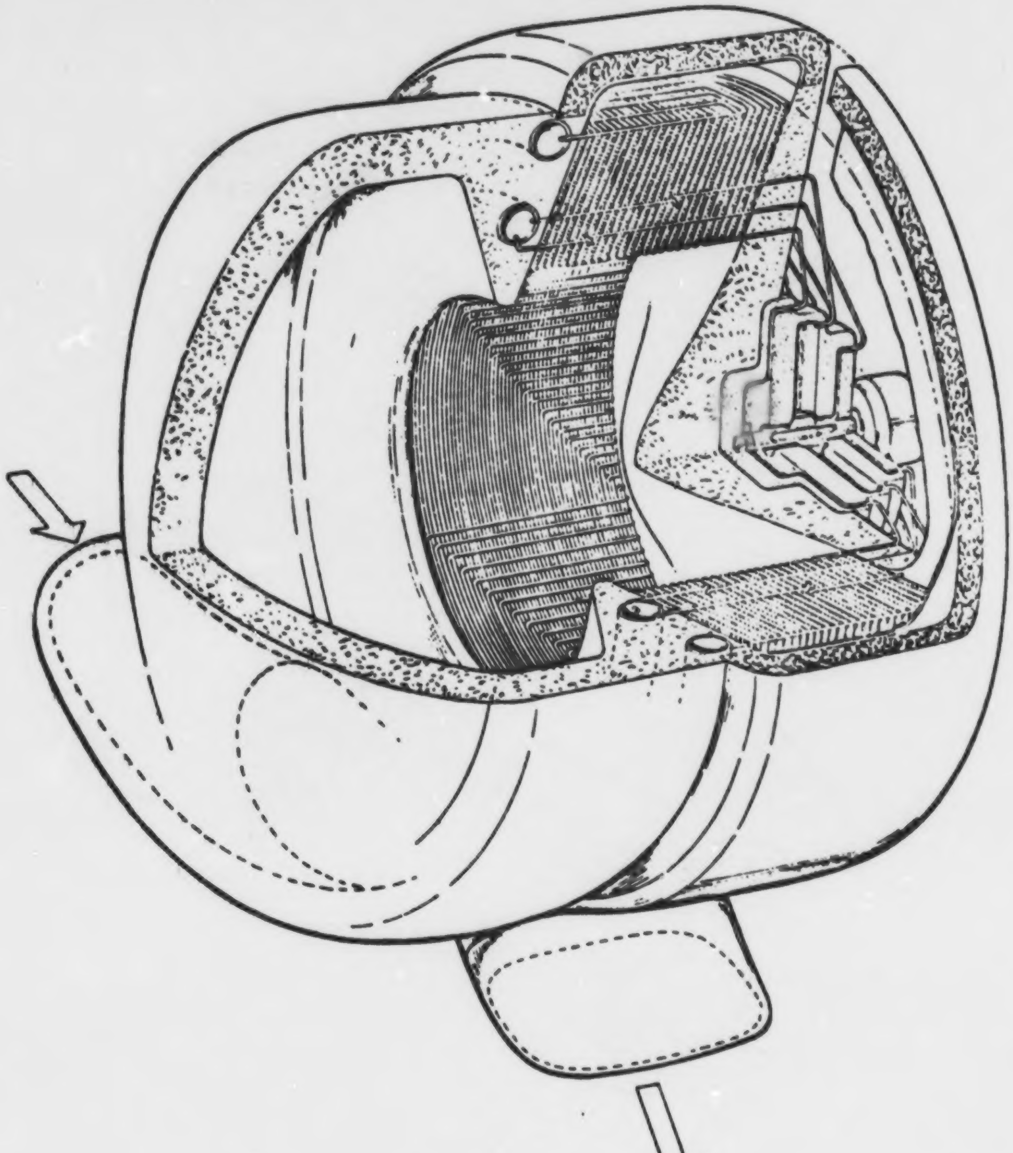


Fig. 108 Steam Generator

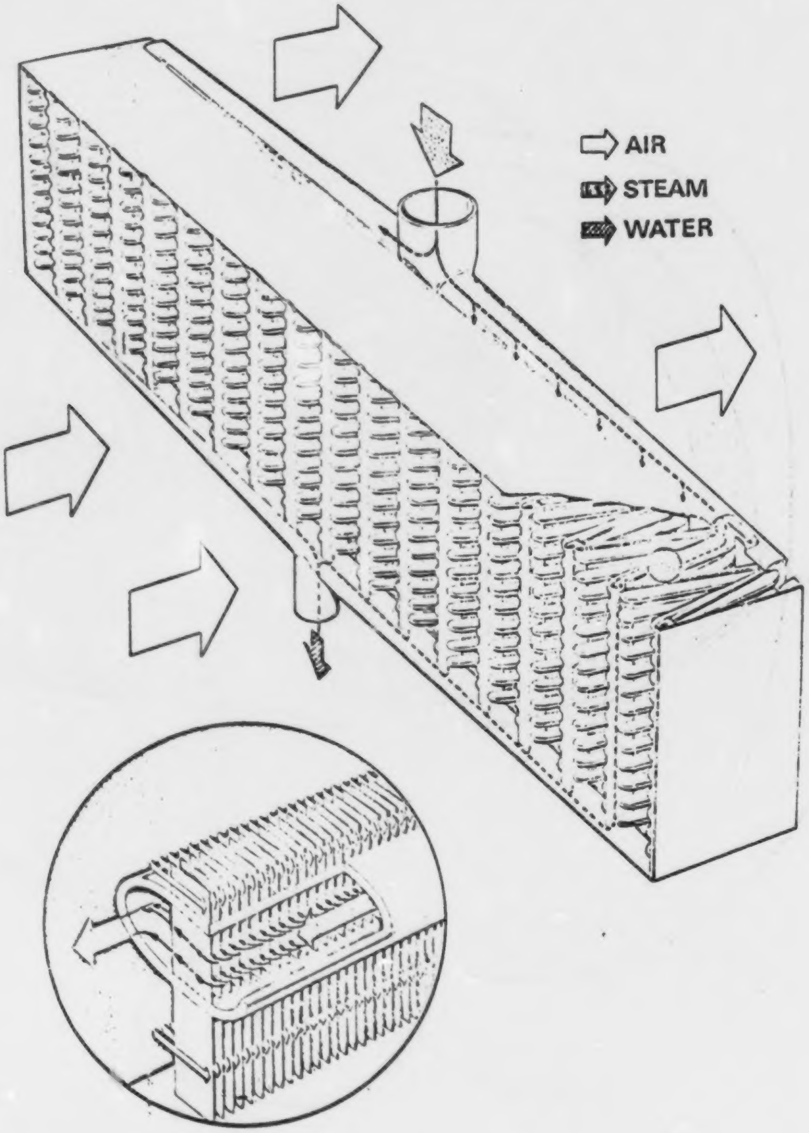

AIR
STEAM
WATER

Fig. 109 Condenser

It is emphasized that the steam power project at Saab-Scania is not in a production condition, and there is no decision to go into production at present.

Points Clarified in Question/Answer Period:

- No plans have been made to build an engine and install it in a car.
- A rotating valve arrangement with variable cut-off is used in the engine. Some tests have been run on valve materials.
- There are test data on the steam generator (heat exchanger part), engine components (cylinder piston rings, 4 valves, condenser, and condenser buffer - there is a heat transfer problem in condenser buffer).
- Hermetically sealed boiler, in U. S. experience, would blow-off due to dissociation of water on hot metal; however, the amount of water is small. Problem was not resolved in the discussion.
- Condenser buffer is to handle peak load (10 - 15 kg. of water storage).
- A 0.3 mm or less fin spacing is used on the condenser.
- No emission measurements have been made on the steam generator.

C. Water Base Reciprocating System Status, by Roger Demler, Program Manager, Scientific Energy Systems, Inc., Watertown, Massachusetts

The objectives are to demonstrate feasibility of a water-base Rankine automotive power plant with a reciprocating expander and to demonstrate improved fuel economy in December 1973.

The system features are as follows:

• Working Fluid	Pure water - 1000°F, 1000 PSIG at boiler exit
• Freeze Protection	Working inventory drained to heated sump on shutdown

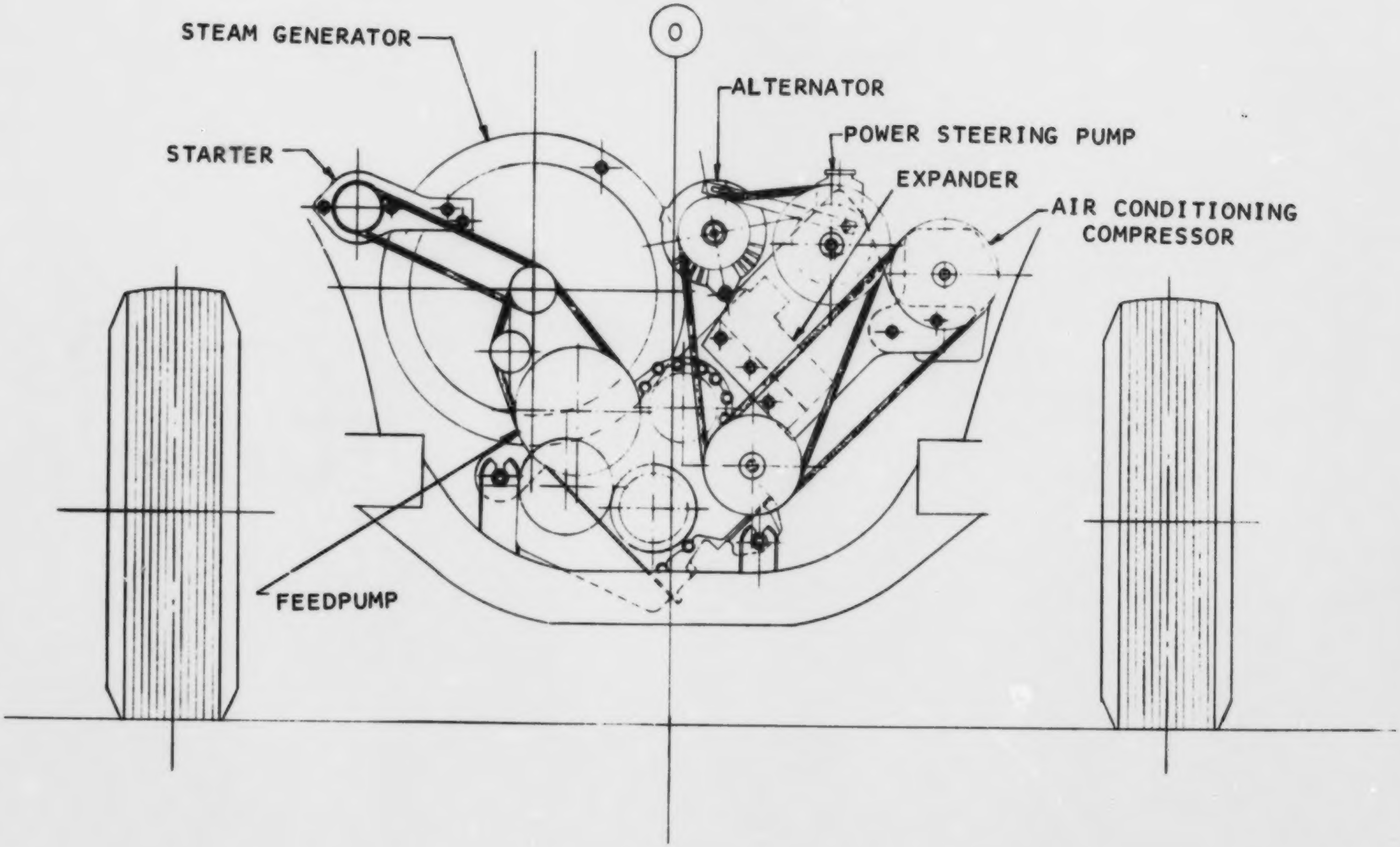
• Reciprocating Expander	4 cyl. in-line - 135 CID, trunk piston, uniflow exhaust, variable cut-off control
• Design Point	EPA/AAPS vehicle specification max steam flow = 20 LB/MIN
• Maximum Expander Power:	(85°F ambient, high gear)
Gross HP	= 158 at 1500 RPM
Net HP into transmission	= 138 at 1500 RPM
• Boiler Heat Input to Water at Max Power	= 1.58×10^6 BTU/HR
• Condenser Heat Rejection at Max Power	= 1.21×10^6 BTU/HR

The program status is:

- Baseline configuration preprototype test completed 175 hours on closed-loop.
- All components and controls are functional.
- Resolution of mechanical problems is near completion.
- Tests in process to define baseline configuration dynamic limitations.
- Higher than predicted expander friction power and blowby are only constraints on achieving predicted system efficiency.
- MOD #1 in process for improved fuel economy.
- Qualification of MOD #1 is scheduled for December 1973.

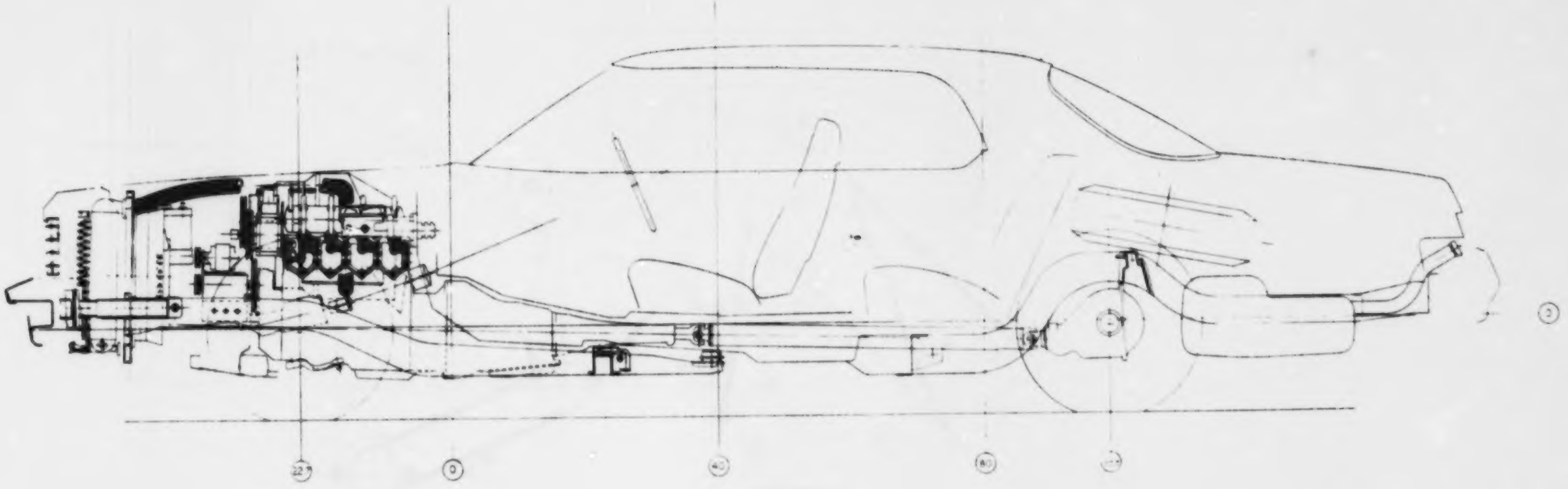
Figures 110 and 111 show this preprototype installation in the Plymouth "C" body, and Fig. 112 shows the actual hardware preprototype system on the test stand.

Revisions of the expander valve to achieve improved fuel economy are shown diagrammatically in Fig. 113. Present and projected fuel economy improvements are shown in Fig. 114. Projected emissions for the Federal Driving Cycle are shown in Fig. 115 as compared to the '76 Standards.


STEAM GENERATOR
STARTER
ALTERNATOR
POWER STEERING PUMP
EXPANDER
AIR CONDITIONING COMPRESSOR
FEEDPUMP
O

PROTOTYPE INSTALLATION
FRONT INTERIOR VIEW
CONDENSER REMOVED
PLYMOUTH "C" BODY

Figure 110



PROTOTYPE INSTALLATION
SIDE SECTION
PLYMOUTH "C" BODY

Figure 111

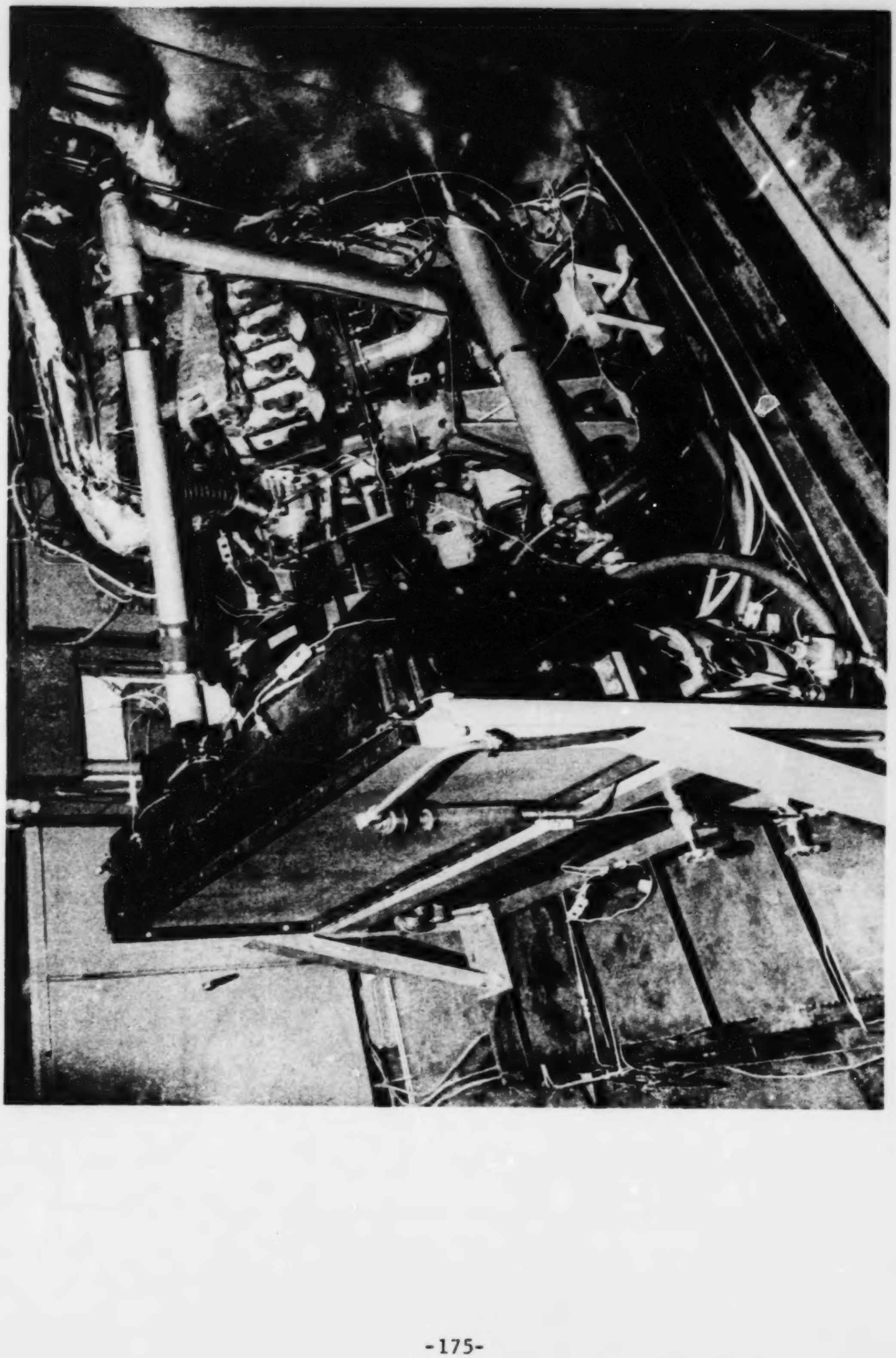


Fig. 112 Preprototype System on Test Stand

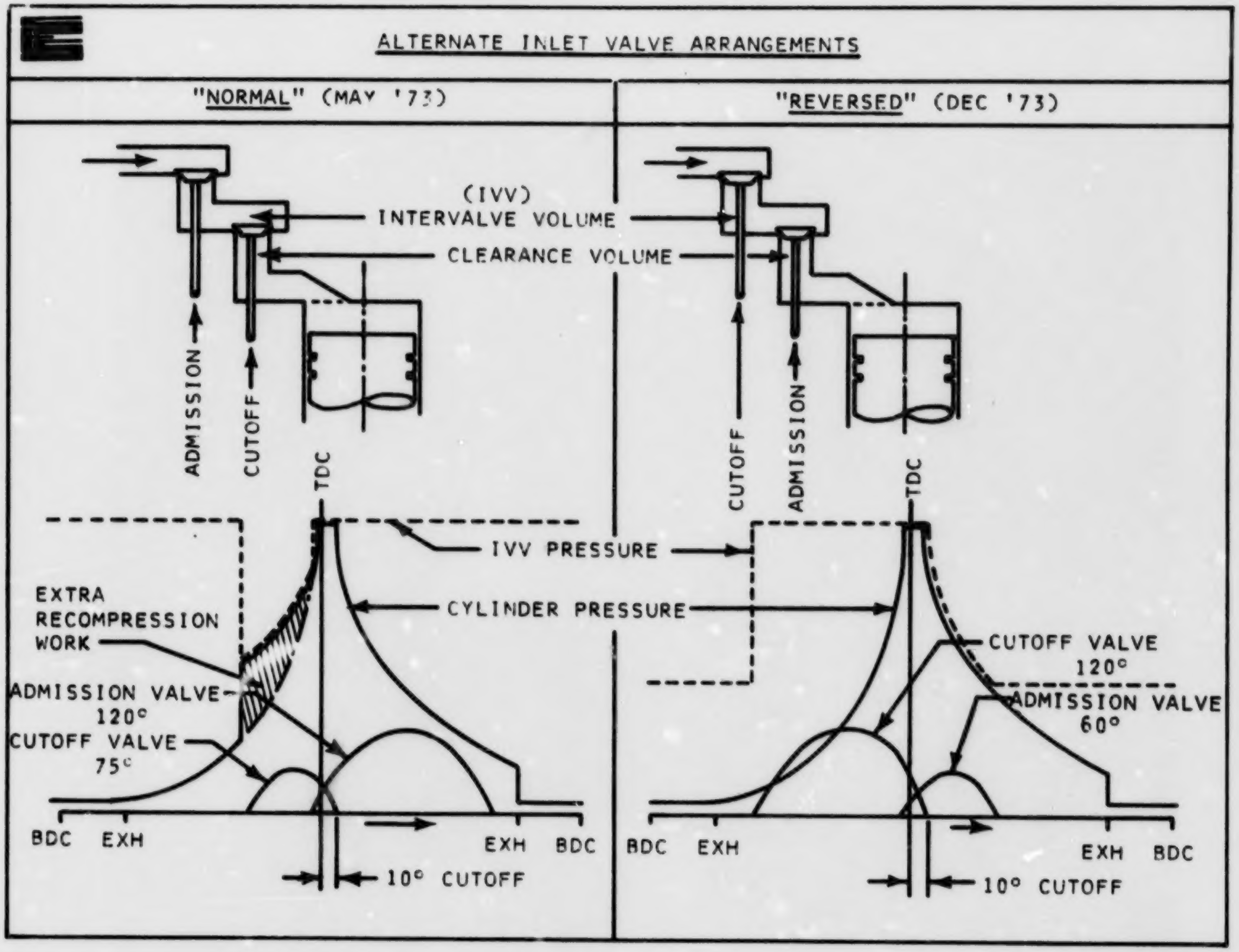

ALTERNATE INLET VALVE ARRANGEMENTS
"NORMAL" (MAY '73)
"REVERSED" (DEC '73)
(IVV)
INTERVALVE VOLUME
CLEARANCE VOLUME
ADMISSION
CUTOFF
TDC
CUTOFF
ADMISSION
TDC
IVV PRESSURE
CYLINDER PRESSURE
EXTRA RECOMPRESSION WORK
ADMISSION VALVE 120°
CUTOFF VALVE 75°
CUTOFF VALVE 120°
ADMISSION VALVE 60°
BDC
EXH
EXH
BDC
10° CUTOFF
BDC
EXH
EXH
BDC
10° CUTOFF

Figure 113

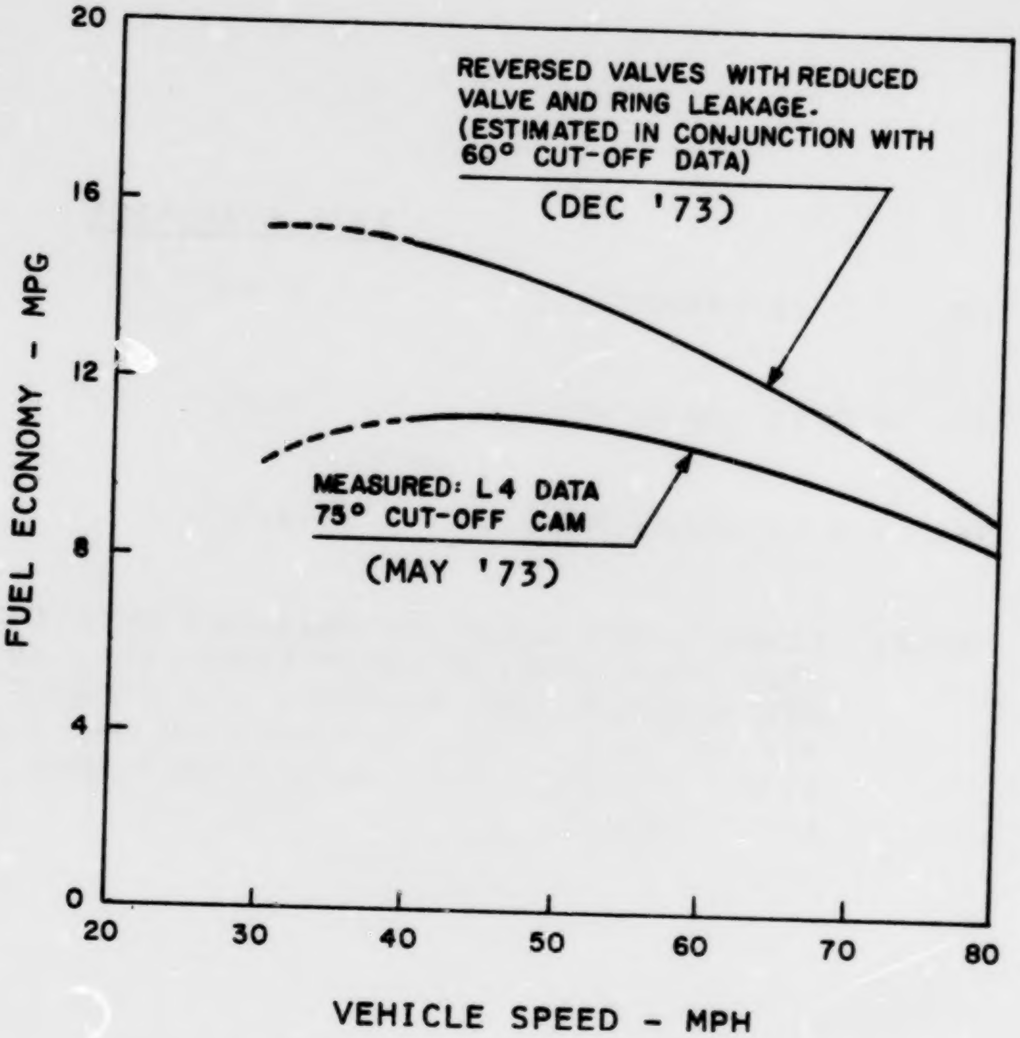


Fig. 114 Fuel Economy Versus Road Speed

	1976 STANDARDS
NO_X = 0.18 GRAMS/MILE	0.40
CO = 0.43 GRAMS/MILE	3.40
UHC = 0.18 GRAMS/MILE	0.41

NOTE: COMPUTATION BASED ON MEASURED EMISSIONS FROM PREPROTOTYPE STEAM GENERATOR, 10 MPG AVERAGE FUEL ECONOMY, 25% AVERAGE FIRING RATE. INCLUDES WARM-UP AND 0.75 GRAMS UHC FOR IGNITION AND SHUT-DOWN EMISSIONS.

Fig. 115 Cold-Start Federal Driving Cycle Emissions

Points Clarified in Question/Answer Period:

- The cylinder liner material is chrome plated by the Vanderhorst Process.
- The expander was designed and made in England.
- The fuel was EPA unleaded gasoline.
- Recognizing that SES is not an automotive production company, it is estimated that production of such an engine could be at least eight years away, given serious interest by the right organization in the near future.
- Piston and liner temperatures reflected about 90% of the design point horsepower. Wear pattern photographs were taken after about 25 hours of operation.
- The uniflow configuration was chosen with the idea of keeping the temperature gradients compatible with the steam flow and to avoid precondensation problems. Requirements for warm-up of a cold or frozen engine (hydrostatic lock-up problems) have not yet been treated.
- Compared with the lacquer, carbon deposits, etc. of an I.C. engine, the lubrication problems, cleanliness, etc. of the steam seem non-existent or trivial.

D. Organic Fluid Reciprocating System, by Jack Armstrong, Assistant Manager, R & D Center, Thermo Electron Corporation, Waltham, Massachusetts

The AAPS Division of EPA is sponsoring part of the development of a low emission Rankine-cycle propulsion system for automobiles at Thermo Electron Corporation (TECO); the Ford Motor Company is also contributing both financially and technically to the development effort.

The system under development at TECO (Fig. 116) uses an organic-based working fluid with a reciprocating expander. The working fluid is Fluorinol-85, a mixture of 85 mole percent trifluoroethanol and 15 mole percent water. The system is designed to provide performance approximately equivalent to a 351 cubic

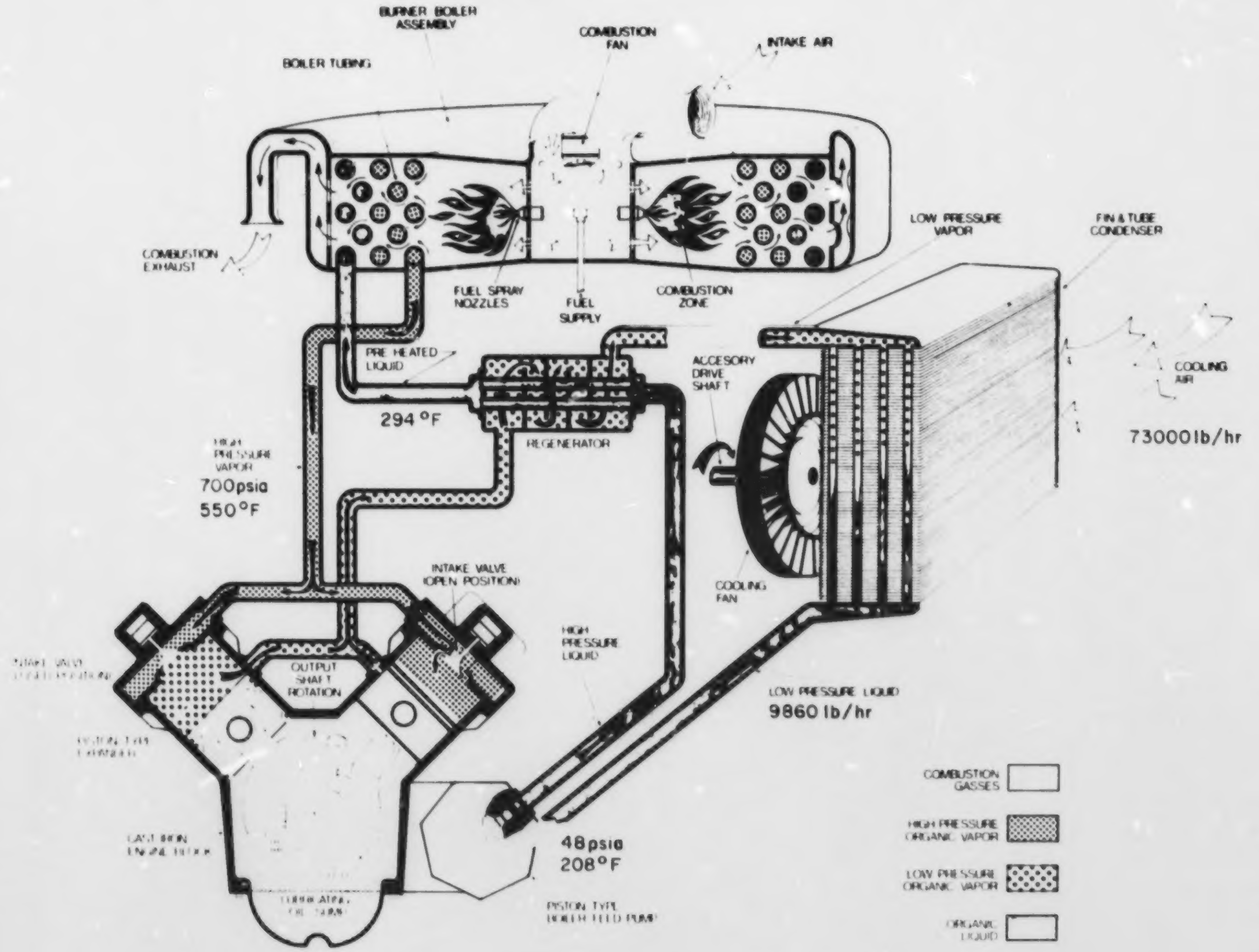

BOILER TUBING
BURNER BOILER ASSEMBLY
COMBUSTION FAN
INTAKE AIR
COMBUSTION EXHAUST
FUEL SPRAY NOZZLES
FUEL SUPPLY
COMBUSTION ZONE
LOW PRESSURE VAPOR
FIN & TUBE CONDENSER
PRE HEATED LIQUID
294 °F
REGENERATOR
ACCESORY DRIVE SHAFT
COOLING AIR
73000 lb/hr
HIGH PRESSURE VAPOR
700psia
550°F
INTAKE VALVE (OPEN POSITION)
COOLING FAN
HIGH PRESSURE LIQUID
EXHAUST VALVE (CLOSED POSITION)
OUTPUT SHAFT ROTATION
PISTON TYPE EXPANDER
LOW PRESSURE LIQUID
9860 lb/hr
CAST IRON ENGINE BLOCK
48psia
208°F
LUBRICATING OIL SUMP
PISTON TYPE BOILER FEED PUMP
COMBUSTION GASSES
HIGH PRESSURE ORGANIC VAPOR
LOW PRESSURE ORGANIC VAPOR
ORGANIC LIQUID

Fig. 116 Thermo Electron Rankine Cycle Engine Schematic Diagram

inch displacement internal combustion engine in the reference car, the 1972 Ford Galaxie.

Over 42 hours of test time has been accumulated on the preprototype system. The current phase of the program involves further development testing of the complete preprototype system in the laboratory, with emphasis on performance and fuel economy improvement.

Data analysis indicates that a significant gain in fuel economy is achievable by improving the performance. Higher expander efficiency, due to improved valving, has been demonstrated in single cylinder expander tests. The modified expander coupled with higher peak temperature (increased from 550 to 625°F) and an improved boost pump schedule, are expected to result in the following emissions, performance, and fuel economy characteristics by December, 1973.

			'76 Standard
Emissions - Federal Driving Cycle	NO_x	.275 gm/mile	0.40
	CO	.21 gm/mile	3.40
	UHC	.17 gm/mile	0.41
0-60 MPH Acceleration Time (85°F Ambient)			13.12 sec.
DOT Passing Time (85°F Ambient)			14.5 sec.
Fuel Economy (85°F)			
30 MPH Steady Speed			16.8 MPG
50 MPH Steady Speed			13.2 MPG
70 MPH Steady Speed			8.5 MPG
Federal Driving Cycle			10.2 MPG

An analysis of an advanced prototype system has been performed. This shows an improved fuel economy over the Federal Driving Cycle of 12.1 MPG along with reduced weight and better packaging. The future, advanced prototype system and the projected fuel economy characteristics are shown in Figs. 117 and 118.

WORKING FLUID	FLUORINOL-51 [49 MOLE % WATER]
MINIMUM PUMPING TEMP.	-28°F
FREEZING POINT	-82°F
MAXIMUM TEMPERATURE	650°F
MAXIMUM PRESSURE	1000 PSIA
MAXIMUM FLOW RATE	5070 LBS./HR.
EXPANDER DISPLACEMENT	100 CID.
BETTER PACKAGING	
TOTAL WEIGHT REDUCTION	450 LBS.
PEAK POWER CYCLE EFFICIENCY IMPROVEMENT OVER DEC. 73 GOAL	25.12%
FUEL ECONOMY IMPROVEMENT OVER DEC. 73 GOAL	34.14%

Fig. 117 Features of Advanced Prototype Design

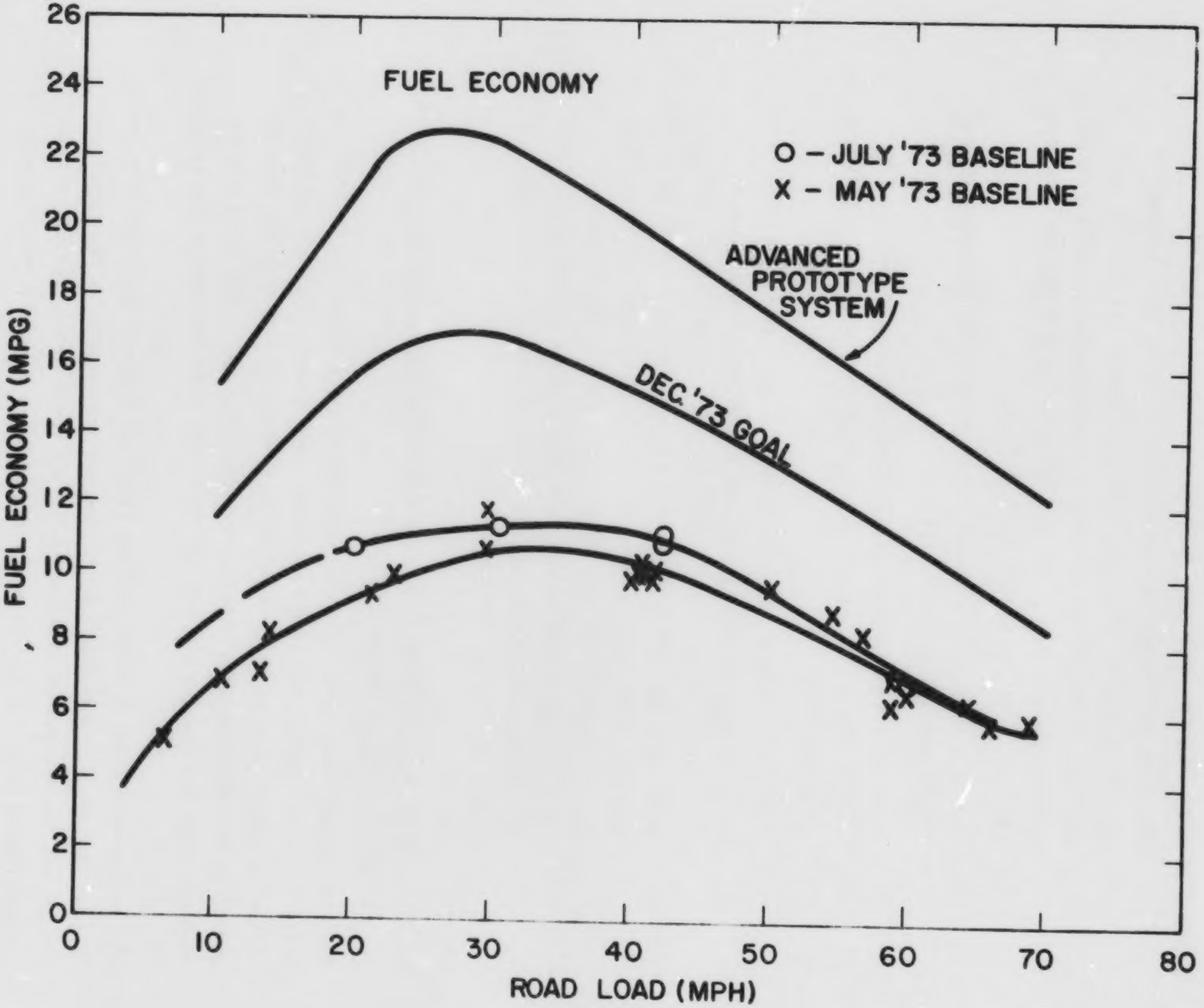


Fig. 118 Current and Projected Fuel Economy

Points Clarified in Question/Answer Period:

- The Ford C-4 automatic transmission is being used because of its availability, low cost, and convenience for vehicle integration. Even though the engine would permit use of a simpler smaller transmission, the cost of developing a special for this program is not warranted at this time.
- Use of a swashplate instead of the conventional crankshaft configuration was not considered.
- A direct drive instead of a transmission should improve fuel economy due to weight saving (perhaps 200 lbs.) and efficiency (perhaps 15%).
- The organic fluids, both Fluorinol 85 and 51, have been undergoing extensive static tests at temperatures and pressures anticipated in the engine and exposed to lubricants and construction materials met in the engine. No decomposition or acid problems have been encountered to date. Static tests run about a year, with inspection every 300 - 400 hours. About 4000 hours of tests in dynamic loops have been run on Fluorinol 85. The fluid is boiled and condensed as it is pumped around under cyclic temperatures and pressures as encountered in an engine.

E. Water Base Turbine System, by Del Hood, Project Manager, and William Lear, President, Lear Motor Company

The EPA contract with Lear has been underway for 9 months. It is based on 5 years of prior Rankine system development. The practicality of the basic system has been established by 2 years of road tests - 8000 miles in a bus and about 4 months and 1000 miles in a Monte Carlo car. The car installation was disassembled for the current dynameter test and evaluation program.

The performance plan is shown in Fig. 119. The project is in its 34th week. To date the major effort has been on further improvement of the vapor generator and the design and development of the computer controlled test and data acquisition facility. This assures accurate input to the 23-minute

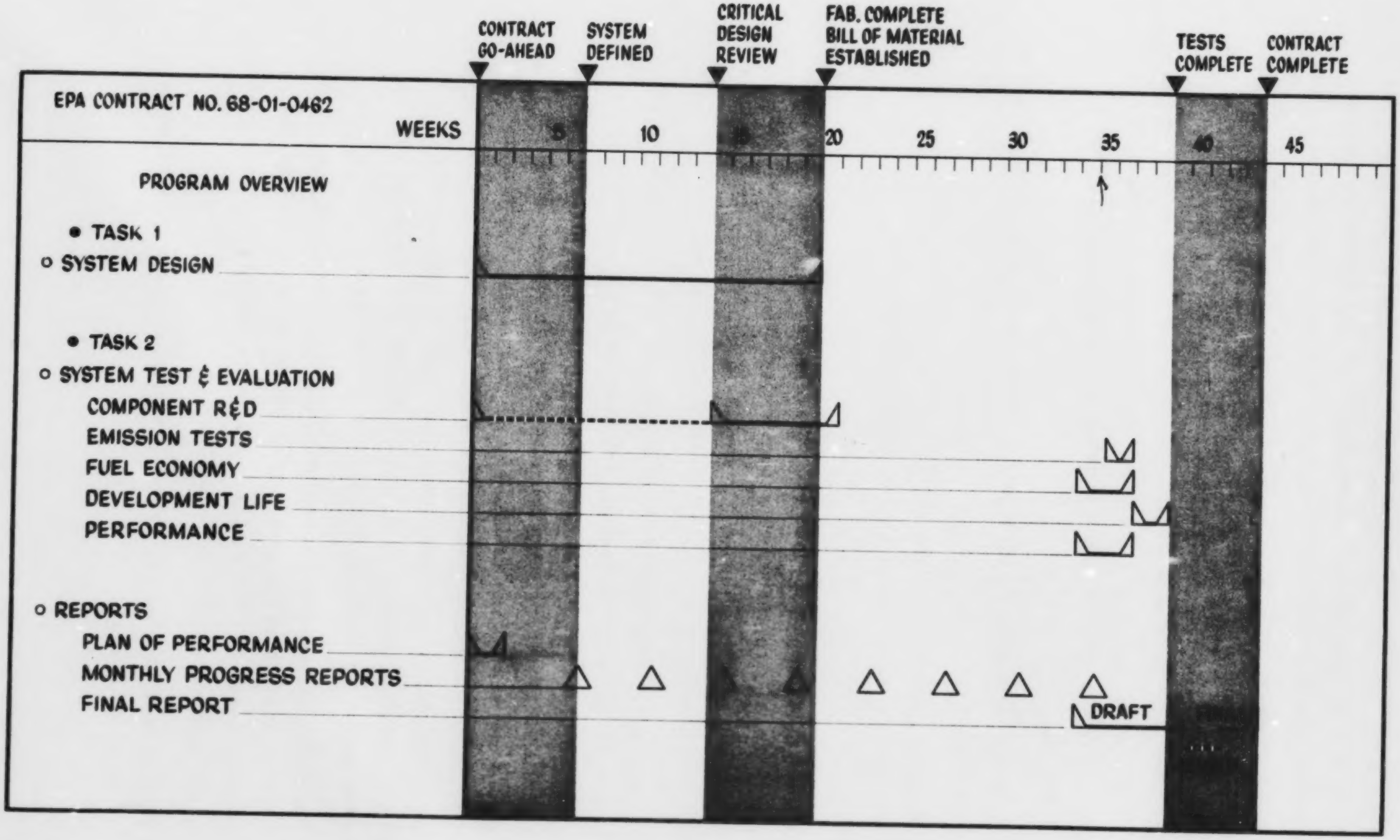


Fig. 119 Performance Plan

Federal Driving Cycle test procedures. Component test and system debugging have been completed. System tests are now being initiated. The design point thermodynamic cycle is shown in Fig. 120; the laboratory schematic is shown in Fig. 121 and photographs of the laboratory installation and the turbine power unit are shown in Figs. 122 and 123. A schematic of the vapor generator is shown in Fig. 124. The data acquisition schematic is shown in Fig. 125. A random plot of emission data taken from the boiler is shown in Fig. 126, indicating that most of the points taken over an extended period of time are below '76 standards.

Comments by Mr. Lear: A number of interesting points were made by Mr. Lear which are appropriate to include:

- The rapid progress to date by LMC on the current program has been greatly facilitated by the close cooperation of General Motors.
- The accomplishments to date are the results of money, time, and energy devoted to the Rankine engine over the last five years by Mr. and Mrs. Lear and their technical staff, who all accepted the challenge of a practical steam vehicle engine.
- It is a major step from development prototypes to a production prototype not only in design, but also in investment and know-how. Involvement of a large production-oriented company such as Ford, Chrysler, or General Motors is essential. It is believed the bus engine development is now ready to enter the production prototype stage. Mr. & Mrs. Lear have invested about $17 million of their personal funds to date on the development. Another $100 million is the estimated investment needed to complete the production prototype.
- Evolution of the current engine design was traced through reciprocating and screw type expanders and heavy fluids to the present steam turbine design. All steps are leading to a lower cost, more producible design.
- Emergence of the energy crisis has prompted some current work on pulverized coal.

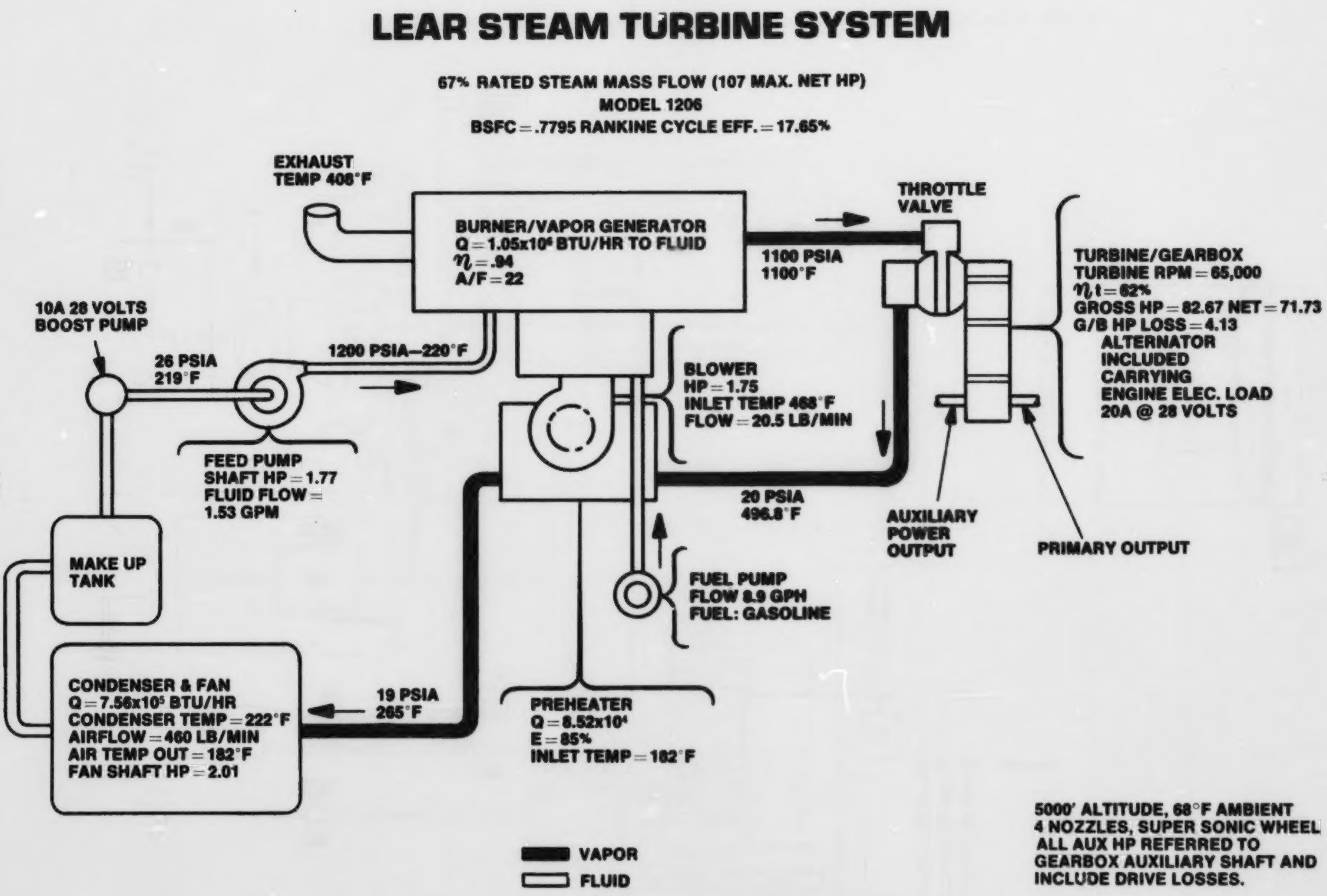

LEAR STEAM TURBINE SYSTEM
67% RATED STEAM MASS FLOW (107 MAX. NET HP)
MODEL 1206
BSFC = .7795 RANKINE CYCLE EFF. = 17.65%
EXHAUST
TEMP 408°F
BURNER/VAPOR GENERATOR
Q = 1.05×10^6 BTU/HR TO FLUID
η = .94
A/F = 22
1100 PSIA
1100°F
THROTTLE
VALVE
TURBINE/GEARBOX
TURBINE RPM = 65,000
η_t = 62%
GROSS HP = 82.67 NET = 71.73
G/B HP LOSS = 4.13
ALTERNATOR
INCLUDED
CARRYING
ENGINE ELEC. LOAD
20A @ 28 VOLTS
10A 28 VOLTS
BOOST PUMP
26 PSIA
219°F
1200 PSIA—220°F
BLOWER
HP = 1.75
INLET TEMP 468°F
FLOW = 20.5 LB/MIN
FEED PUMP
SHAFT HP = 1.77
FLUID FLOW =
1.53 GPM
20 PSIA
496.8°F
AUXILIARY
POWER
OUTPUT
PRIMARY OUTPUT
MAKE UP
TANK
FUEL PUMP
FLOW 8.9 GPH
FUEL: GASOLINE
CONDENSER & FAN
Q = 7.56×10^5 BTU/HR
CONDENSER TEMP = 222°F
AIRFLOW = 460 LB/MIN
AIR TEMP OUT = 182°F
FAN SHAFT HP = 2.01
19 PSIA
265°F
PREHEATER
Q = 8.52×10^4
E = 85%
INLET TEMP = 182°F
5000' ALTITUDE, 68°F AMBIENT
4 NOZZLES, SUPER SONIC WHEEL
ALL AUX HP REFERRED TO
GEARBOX AUXILIARY SHAFT AND
INCLUDE DRIVE LOSSES.
VAPOR
FLUID

Fig. 120 Design Point Thermodynamic Cycle

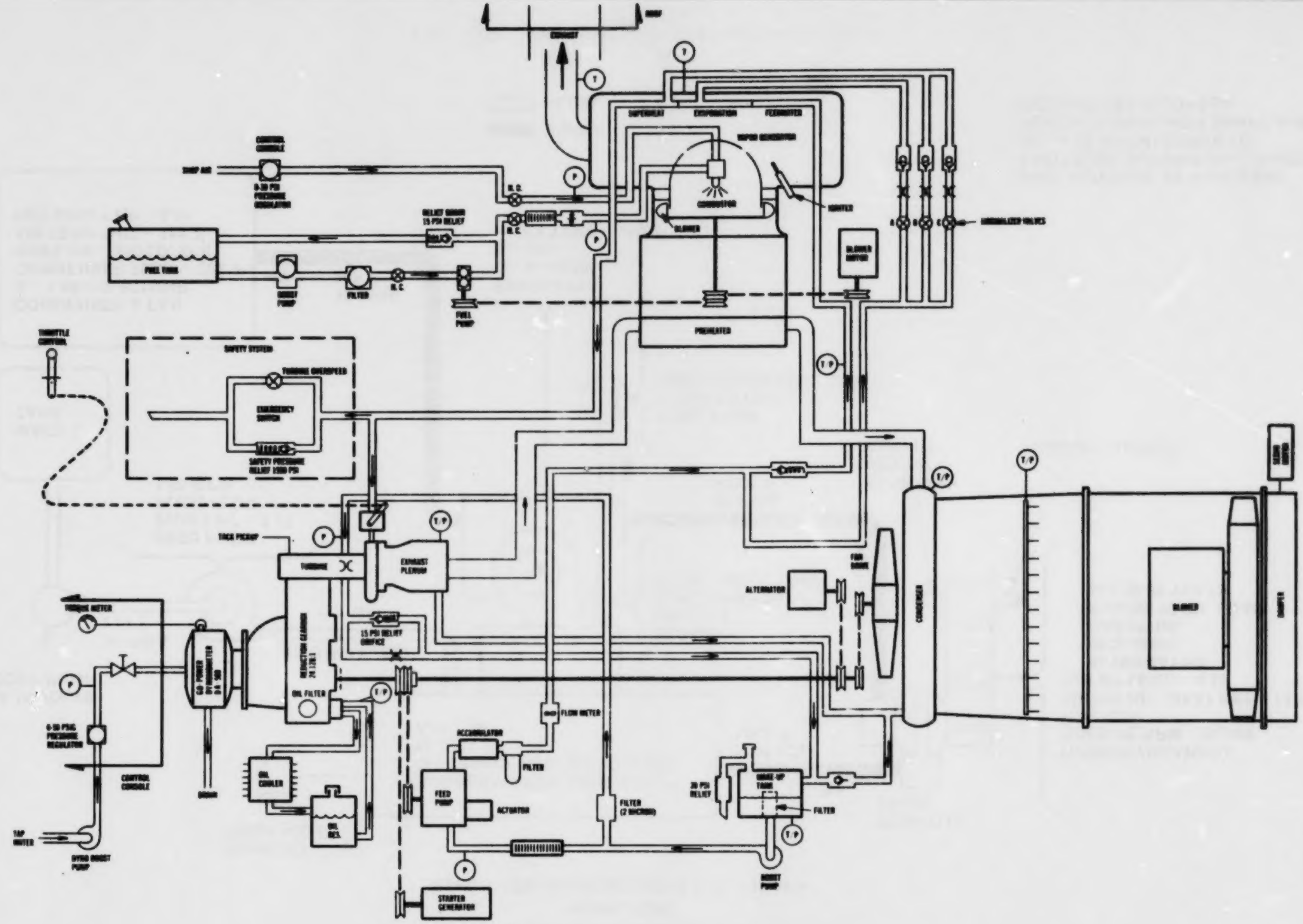

EXHAUST
T
P
SUPERHEAT
EVAPORATION
FEEDWATER
VAPOR GENERATOR
COMBUSTOR
IGNITER
BLOWER
BLOWER MOTOR
PREHEATER
A
B
C
CONTROL CONSOLE
SHOP AIR
0-30 PSI PRESSURE REGULATOR
N.C.
RELIEF VALVE 15 PSI RELIEF
FUEL TANK
BOOST PUMP
FILTER
FUEL PUMP
THROTTLE CONTROL
SAFETY SYSTEM
TURBINE OVERSPEED
EMERGENCY SWITCH
SAFETY PRESSURE RELIEF 2300 PSI
TACH PICKUP
TURBINE
EXHAUST PLENUM
T/P
15 PSI RELIEF ORIFICE
REDUCTION GEARBOX
OIL FILTER
TORQUE METER
DYNAMOMETER
0-30 PSIG PRESSURE REGULATOR
CONTROL CONSOLE
TAP WATER
BOOST PUMP
DRAIN
OIL COOLER
OIL RES.
FLOW METER
ACCUMULATOR
FILTER
FEED PUMP
ACTUATOR
STARTER GENERATOR
FILTER (2 MICRON)
20 PSI RELIEF
MAKE-UP TANK
FILTER
BOOST PUMP
ALTERNATOR
FAN DRIVE
CONDENSER
BLOWER
DAMPER
SERVO MOTOR

Fig. 121 Laboratory System Schematic for Tests According to EPA Requirements

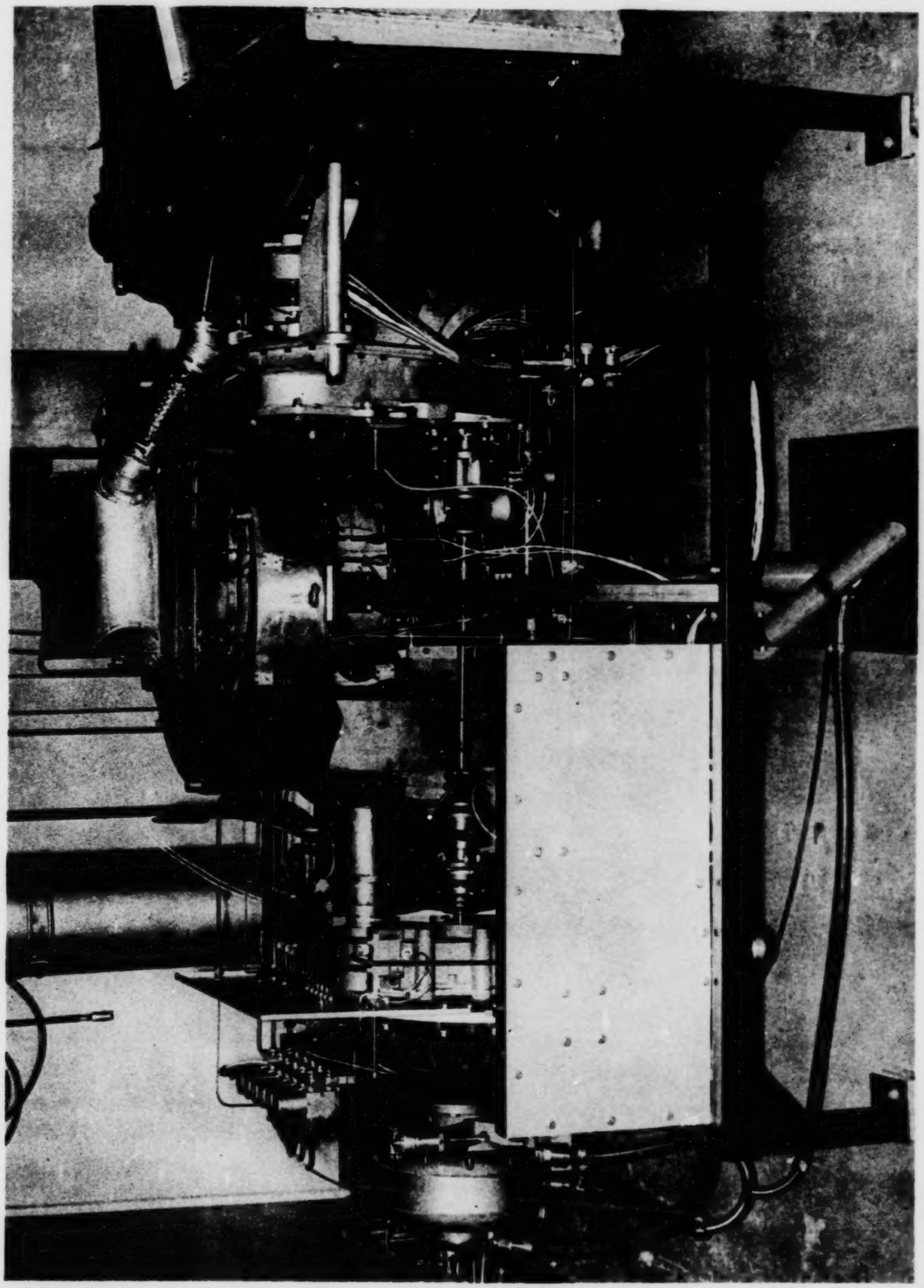


Fig. 122 Laboratory Installation

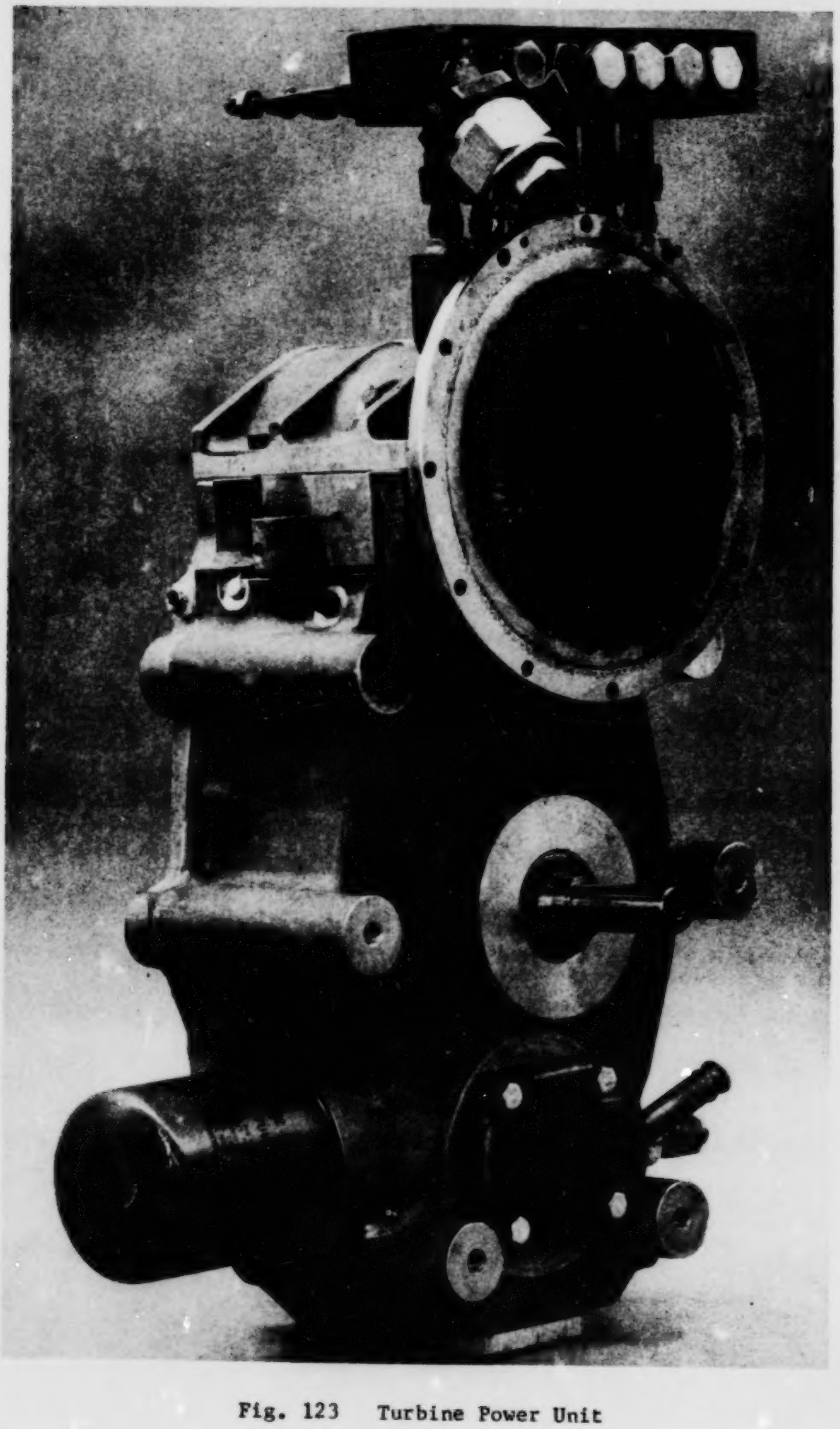


Fig. 123 Turbine Power Unit

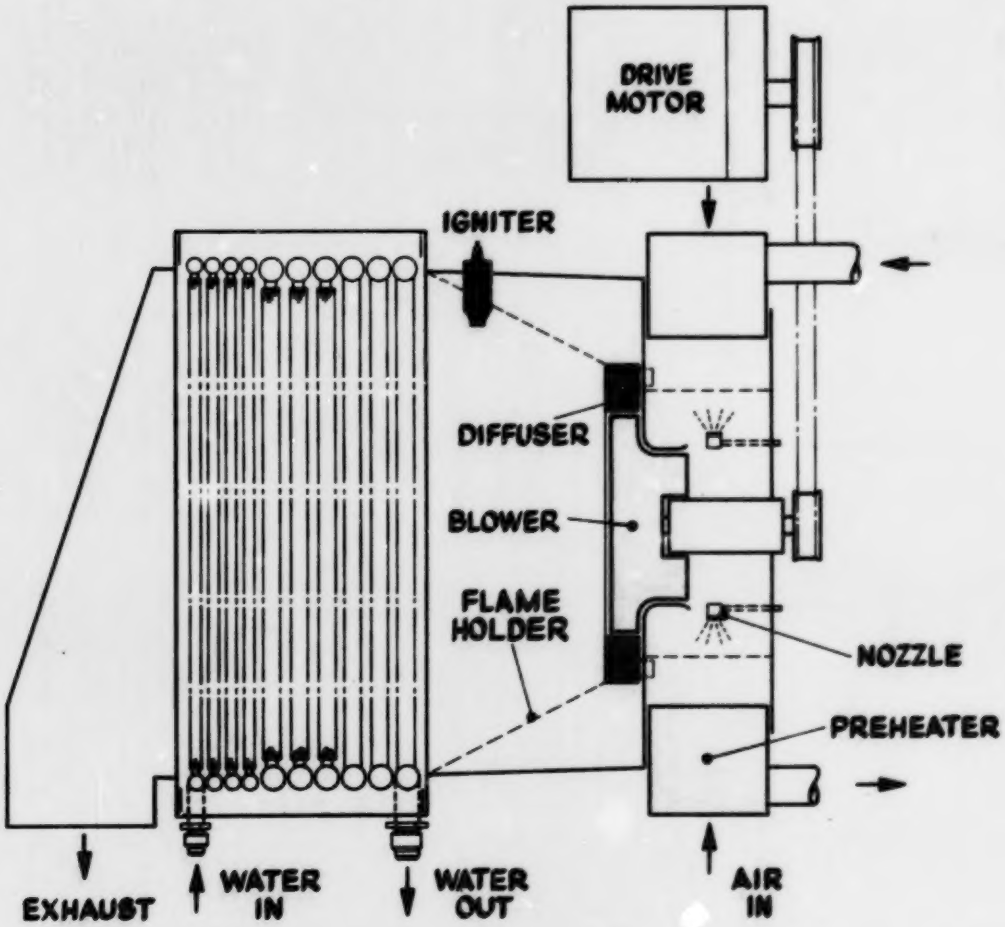

DRIVE MOTOR
IGNITER
DIFFUSER
BLOWER
FLAME HOLDER
NOZZLE
PREHEATER
EXHAUST
WATER IN
WATER OUT
AIR IN

Fig. 124 Vapor Generator Assembly

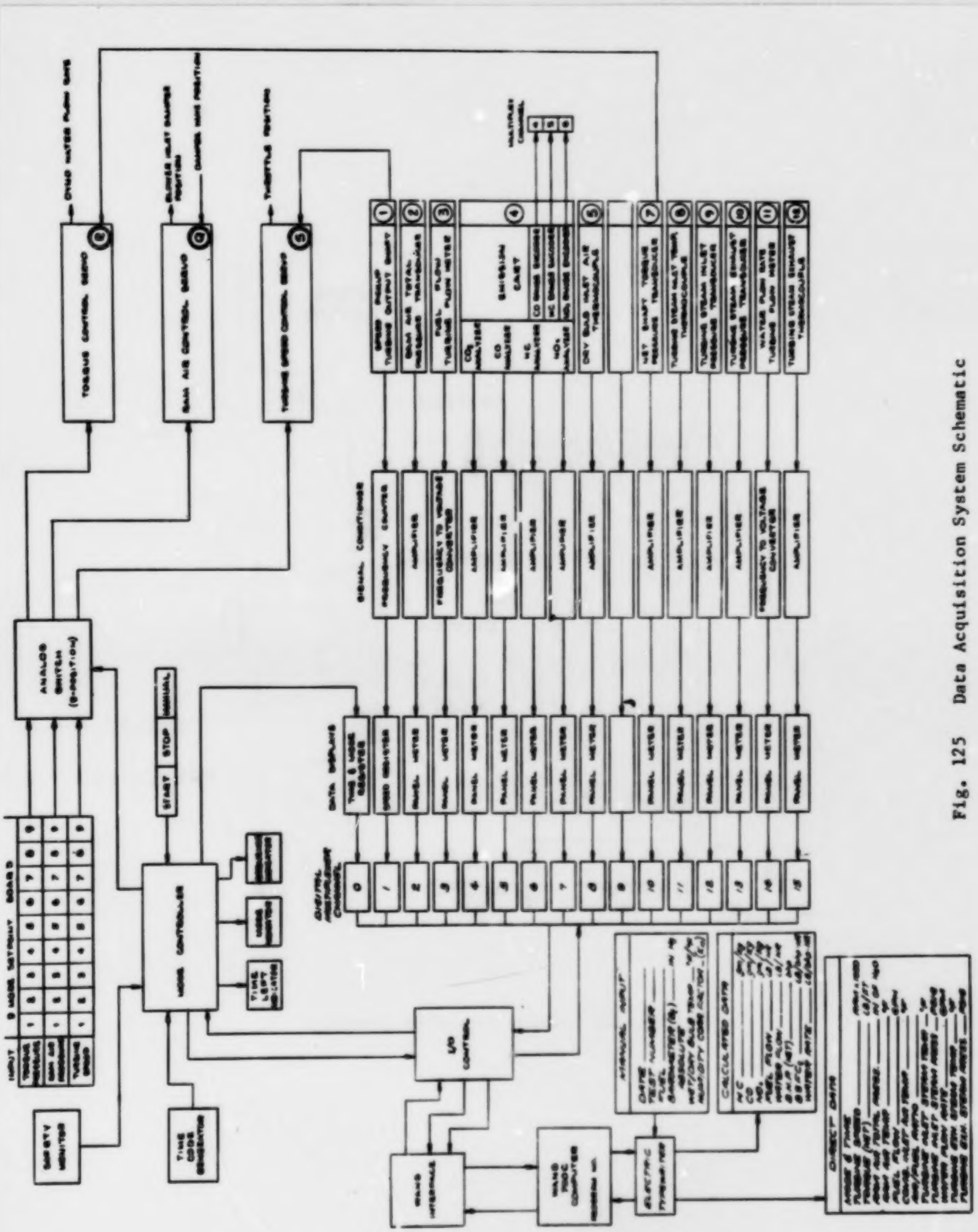

INPUT
9 MODE SETPOINT BOARD
TORQUE
RAM AIR
TURBINE SPEED
ANALOG SWITCH (3-POSITION)
TORQUE CONTROL SERVO
RAM AIR CONTROL SERVO
TURBINE SPEED CONTROL SERVO
DYNO WATER FLOW RATE
BLOWER INLET DAMPER POSITION
DAMPER VANE POSITION
THROTTLE POSITION
SAFETY MONITOR
MODE CONTROLLER
START
STOP
MANUAL
TIME LEFT INDICATOR
TIME CODE GENERATOR
I/O CONTROL
WANG INTERFACE
WANG 720C COMPUTER
ELECTRIC TYPEWRITER
DIGITAL INSTRUMENT CHANNEL
DATA DISPLAYS
TIME & MODE REGISTER
SPEED REGISTER
PANEL METER
SIGNAL CONDITIONERS
FREQUENCY COUNTER
AMPLIFIER
FREQUENCY TO VOLTAGE CONVERTER
EMISSION CART
MULTIPLEX CHANNEL
MANUAL INPUT
CALCULATED DATA
DIRECT DATA

Fig. 125 Data Acquisition System Schematic

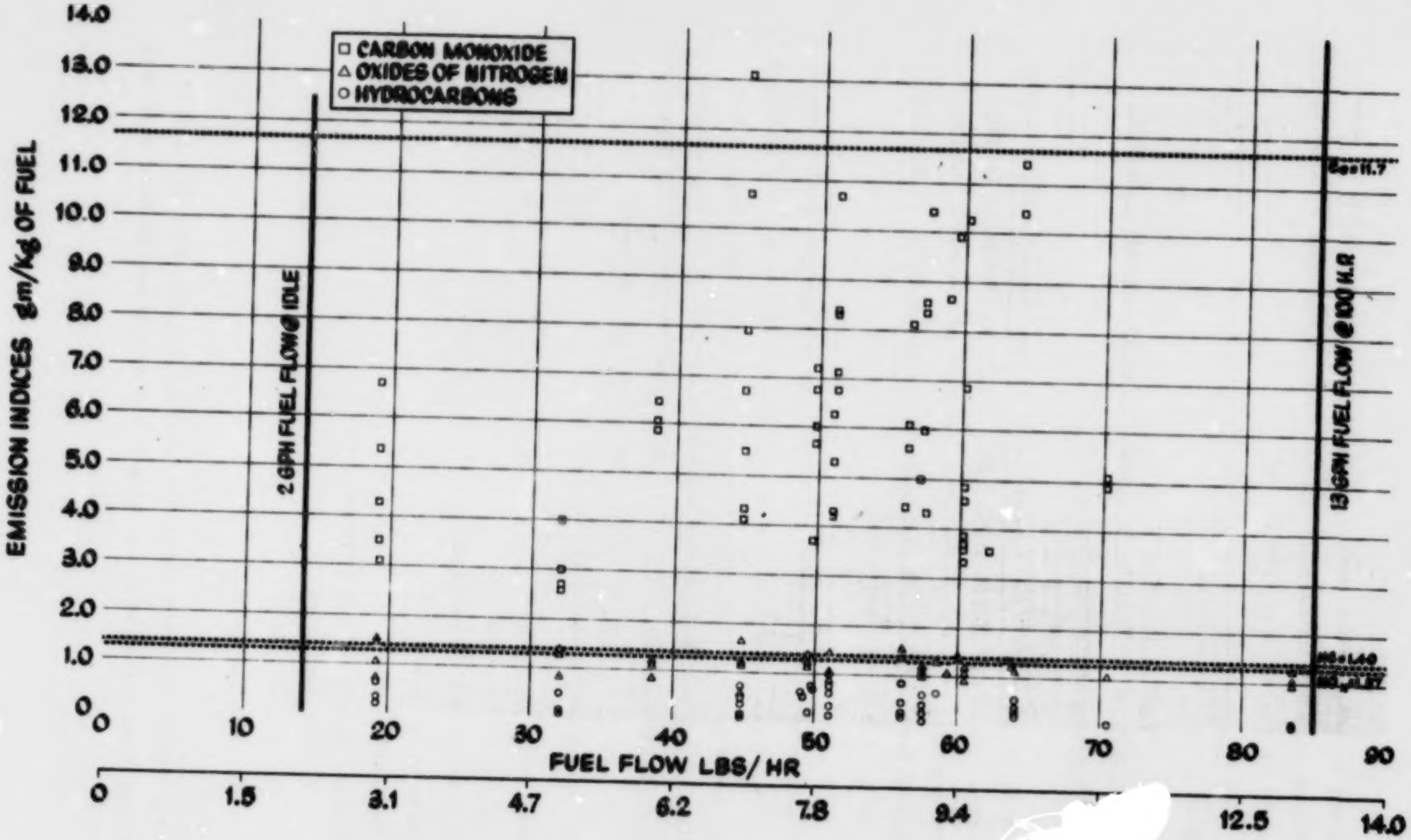


Fig. 126 Emission Versus Fuel Flow

- Based on present test work, an automotive steam engine is projected with low pollution, capable of a 17 MPG fuel economy for a 100 HP engine in a 4500 lb car.

Questions: None

F. Organic Fluid Turbine System, by Al Kreeger, Program Manager, Aerojet Liquid Rocket Co., Sacramento, California

Aerojet Liquid Rocket Company (ALRC) began work on the organic Rankine cycle automotive engine for EPA in March 1971. Program accomplishments to date include system synthesis studies, selection and test of a working fluid, engine design and fabrication, and preprototype engine testing. The engine is designed for a 1973 Chevrolet sedan.

The ALRC automotive engine operates with a proprietary working fluid designated AEF-78. The fluid has demonstrated superior thermal stability in tests of several thousand hours. The prime mover is a single-stage, axial flow impulse turbine using variable partial admission control. The engine operates on a regenerative, super critical cycle. Super critical operation provides system stability and alleviates the danger of hot spots. Basic engine operating characteristics are as follows:

Peak cycle temperature	= 650°F
Peak cycle pressure	= 1000 psia
Heat rejection temperature	= 250°F
Maximum net power	= 120 HP
Peak fuel economy	= 16 mpg

Federal Driving Cycle Emissions:

NO_x = 0.149 gm/mi
CO = 0.317 gm/mi
HC = 0.053 gm/mi

A preprototype engine has been built and tested. Engine tests lasting 53 hours were conducted during which component and system performance maps were generated. Emissions data were excellent, less than 1/2 EPA goals. Components identified for further assessment and improvement were the working fluid pump and turbine. Other than these components, engine performance met expectations. Design improvements to the pump and turbine have been identified. (See Figs. 127 and 128). Anticipated fuel economy is shown in Fig. 129.

The following conclusions are drawn from the program progress and achievements to date:

- Emission goals can be met with no difficulty.
- The ALRC organic working fluid is capable of operating at 650°F and above.
- The working fluid seal system is effective.
- The prototype engine with modified components will meet fuel economy and performance specifications.
- The engine can be packaged in a standard vehicle engine compartment without major modifications.

Points Clarified in Question/Answer Period:

- Differences between the ALRC and Lear turbine speeds and fuel economy characteristics stem largely from the different types of working fluid - organic and water.
- The reason the turbine shaft seal is so important is that it prevents the hydraulic fluid (used as a gear box lubricant) from mixing with the organic working fluid which drives the turbine. If this did occur, the lower thermal stability of the hydraulic fluid would lead to fouling in the vapor generator and result in local hot spots. These in turn could expose the working fluid to temperatures beyond its stability limits and cause general fouling and failure of the machine.

- CHANGE TO FIXED DISPLACEMENT GEAR PUMP
- USE 2 PUMPS IN SERIES AT LOW FLOW AND IN PAPALLEL AT HIGH FLOW
- USE VARIABLE SPEED DRIVE

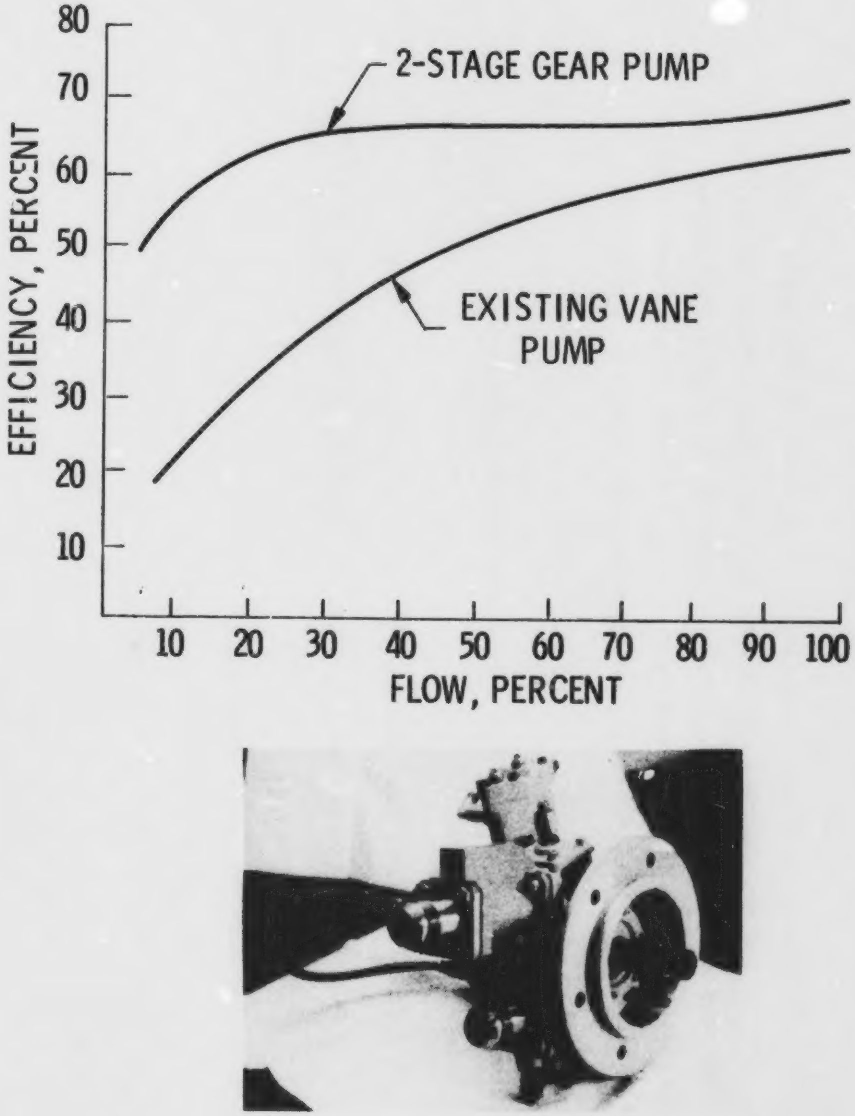
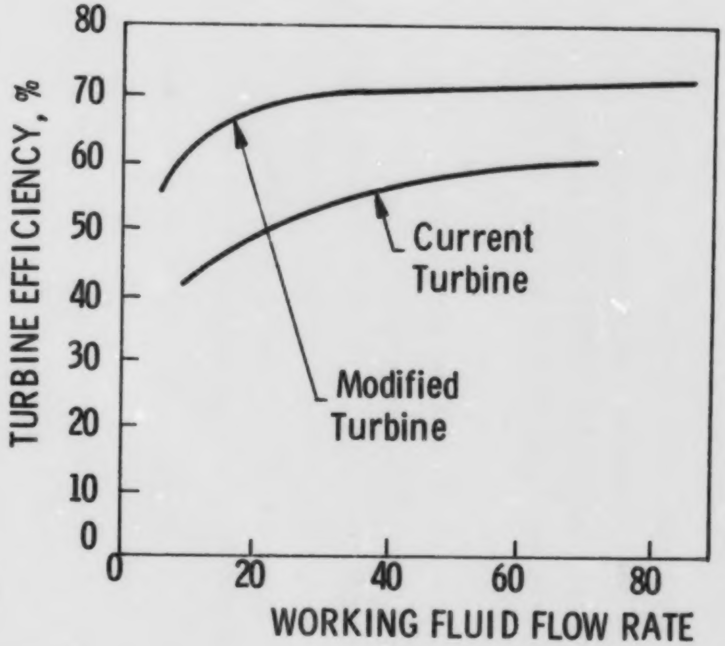


Fig. 127 Feedpump Design Changes

DESIGN MODIFICATIONS

- REDUCE PARTIAL ADMISSION LOSSES-ELIMINATE SPLIT ARCS OF ADMISSION
- NOZZLE
  - REDUCE THROAT ASPECT RATIO
  - SMOOTH CONTOUR
- ROTOR
  - REDUCE LEADING & TRAILING EDGE THICKNESSES
  - DECREASE INCIDENCE ANGLE
  - INCREASE TURNING



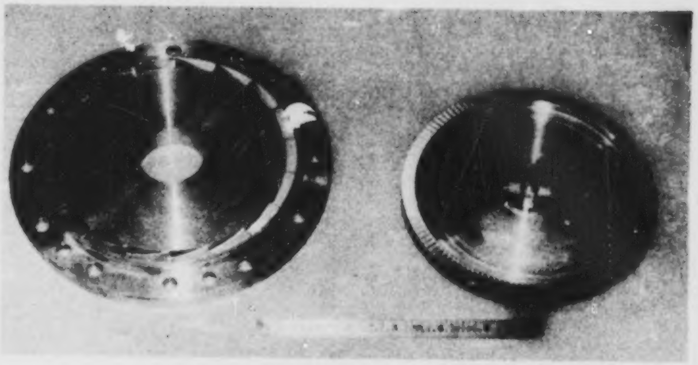


Fig. 128 Turbine Design Modifications

- The ALRC system power (for a full size car) is nominally limited by frontal area available for the condenser. It would be easier to get a higher horsepower/weight ratio in a smaller car because, in scaling down the frontal area does not decrease as fast as the weight of the car.
- The effect of finite step variations in turbine nozzle area (rather than continuously modulated flow) is barely noticeable in driving the car. (It is like the shift point in an automatic transmission.) Turbine nozzle pressure varies between 1000 PSI and 600 PSI as the various valves open. The system and efficiency are relatively insensitive to these variations.
- Only a very simple approach to the cost has been taken so far. Except for the turbine wheel itself, all of the engine materials are low cost, low alloy steels similar to those used in conventional automotive engines. Since the Rankine engine may be about 200 - 300 lbs heavier, the cost will probably increase only by a similar ratio.
- Residual hydrogenated hydrocarbon fluids and other organic Rankine fluids in discarded junk cars could possibly represent a hazard to the environment. EPA recognizes this as a possible problem and is working on it with EPA toxicity specialists at Durham, North Carolina.
- Typical design trade-offs in Rankine systems include: regenerator size vs. fuel economy and molecular weight of the fluid; fan power vs. engine efficiency and power and frontal area of condenser. Such trade-offs lend themselves to computer optimization analysis.
- Until recently, fuel economy was not a priority item. Current test data show that '76 emission standards can be met with Rankine systems with fuel economy equal to or better than conventional gasoline engines with controls to meet only '75 standards.

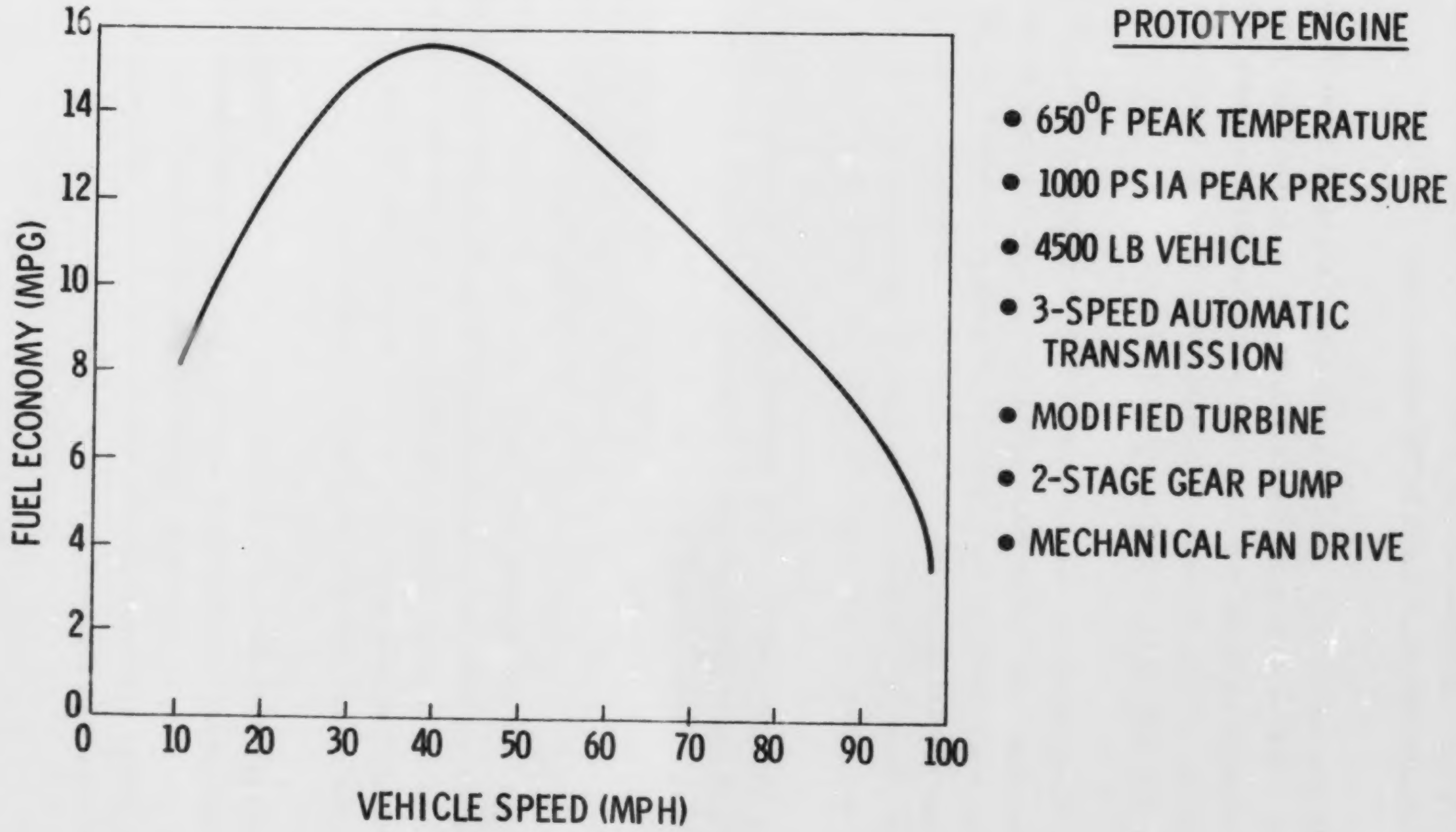


Fig. 129 Prototype Engine Fuel Economy Performance

G. California Clean Car Program, by Mike Wenstrom, Program Manager, California State Assembly, Sacramento and Roy Renner, Consultant

Two Rankine cycle systems will be tested in subcompact automobiles suitable for urban driving. The objective of the California State Assembly in supporting this program is to prove the viability of a low-emission power plant in a compact vehicle. If the concept shows sufficient promise, further development work and supporting legislation could result.

The project has recently passed the mid-point of the development and installation phase of the work. Two California contractors, Aerojet Liquid Rocket Company and Steam Power Systems, Inc., each began work on November 15, 1972 to develop a steam propulsion system for a subcompact automobile. May 15, 1974 is the target date for delivery of the cars to the Assembly. Phase II of the program, beginning in the summer of 1974, will evaluate the cars.

Both contractors have now fabricated or received initial versions of the major components of their power systems. These components are now being tested and improved. System tests will begin in November and December of this year. Installation into the vehicles will take place during the late winter or early spring of 1974.

Design Approaches: The guidelines established for the contractors recognize that a conservative approach was needed in conducting the engineering work due to limitations in time and funds. For example, given the choice between achieving low exhaust emissions or good fuel economy, it was decided to concentrate on the former, leaving the latter for future work.

Aerojet's powerplant will feature a single-stage impulse steam turbine, driving through a hydrostatic transmission manufactured by Allgaier Company of Uhingen, Germany. A steam generator, built by Scientific Energy Systems and based on a design developed for the EPA, will be used. Low-emission characteristics have already been validated by test.

SPS is building a four cylinder, double-acting, compound-expansion steam engine. Power is delivered through a two-speed automatic mechanical transmission. The steam generator, supplied by the Solar Division of the International Harvester Company, was also developed under contract to the EPA.

Figure 130 summarizes some of the design characteristics and expected performance of the two cars.

Points Clarified in Question/Answer Period:

- The first rotating condenser delivered had some development problems in that it did not pump enough air; hence, SES implemented the conventional back up system. The Donbar Company is continuing parallel development, and if the problems can be overcome in time, it will be reconsidered. Tests to date showed low noise and the continued promise of low fan horsepower.
- Mr. Underwood still registered little confidence in the ultimate success of Rankine systems, and inquired about the legality of driving a steam-powered car in Michigan without a steam-engineer's license and with a boiler not built according to the ASME Boiler Code.

	Aerojet	**SPS**
Vehicle		
Type	Chevrolet Vega	Special Construction
Wheelbase, in	97	100
Curb Weight, lb (wet)	2,750	2,850
Gross Weight, fully-loaded, lb.	3,500	3,600
Power System		
Expander rated gross hp	60	65
Expander rated rpm	60,000	2,400
Max. fuel rate, lb/hr	50	48
Expander inlet pressure, psia	500	1,000
Steam temperature, F	1,000	800
Condenser frontal area, ft	4.1	6.1
Condenser thickness, in.	4.5	3.6
Powerplant wet weight, lb	821	850
Expected Performance		
Emissions, CO, g/mi*	0.24	0.42
" HC, " *	0.06	0.07
" NOx " *	0.14	0.19
Urban fuel mileage, mpg*	10.2	11.6
Best fuel mileage, mpg	16	17
Max. speed, 0% grade, mph	75	84
Max. speed, 5% grade, mph	50	57

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* Over Federal Driving Cycle

Fig. 130 Vehicle Characteristics

V. STRATIFIED CHARGE ENGINES

A. EPA Program Status, by Donald Plungis, Project Engineer, Test and Evaluation Branch, EPA

The Test and Evaluation Branch has been testing and evaluating three different stratified charge engines: Ford Proco (Programmed Combustion), TCCP (Texaco Controlled Combustion Process), and the Honda CVCC (Compound Vortex Controlled Combustion). More details and illustrations of these engines are given in Section VII-B and C.

Stratified charge engines have been defined as I.C. engines which use some form of heterogenous fuel-air mixture gradient in the process of combustion. It is characterized by fuel injection and a locally rich region which tends to burn cooler without generating large amounts of NO_x. With high vorticity and turbulence as the combustion process progresses, the excess air from the lean region reacts with the unburned hydrocarbons and the carbon monoxide from the rich region to reduce concentrations of those constituents. With proper design, wall quench hydrocarbons can also be avoided.

Advantages of stratified charge engines include: minimum breathing losses, no manifold distribution problems, lean partload operation, and load control due to the fuel injection. Also the engines have indirectly high mechanical octane ratings and hence have milti-fuel capability; gasoline can be burned at higher compression ratios for better fuel economy. Emissions are inherently lower than those of conventional engines.

Several of these engines have been installed in Army vehicles and a postal van as described below. Although emissions are inherently low, controls are still needed to meet standards. These include part load inlet throttling for HC control, catalysts for CO and HC control, retarded ignition and exhaust gas recirculation for NO_x control Emissions come close to meeting '76 standards with reasonable fuel economy (about 19 mpg). Low NO_x levels seem to adversely affect fuel economy.

EPA is initiating a project with four Capri (Chevrolet) vehicles. Three of these will have Ford Proco engines installed; the fourth is to have a TCCP engine. In addition to the normal NO_x, UHC and CO measurements, aldehydes will be measured, gas chromatograph and odor measurements will be made. Particulates will be measured; smoke is sometimes encountered with stratified charge engines. Effect of mileage accumulation will be studied on two of the vehicles.

As a matter of policy, this group at EPA welcomes the opportunity to test and evaluate specially equipped vehicles from manufacturers as they are made available.

Points Clarified During Question/Answer Period:

- No smoke measurements have been made; they are planned for the Capri vehicles.
- Typically, stratified charge engines have "soft" combustion unlike Diesel engines. Hence, they are quieter.
- The M151 TCCP engine had a thermal reactor and two catalytic reactor. These seem to be needed; however, it was pointed out that this unit was not designed for emission control. Present feeling is that some type of after treatment will be required even if engine was designed and optimized for emission control.
- The Proco vehicle weighs 2500 lbs; the TCCP vehicle weighs 2750 lbs.
- The TCCP car met standards after 50,000 miles with the catalyst changed at 30,000 miles.
- Emission-tuned engines stay just lean of stoichiometric fuel-air ratios at wide open throttle.

B. U. S. Army Tank Automotive Program, by David G. Raggio, Project Engineer

The Army Tank-Automotive Command has been actively investigating HYBRID combustion systems or stratified charge engines since 1963. The original interest resulted from the need to reduce the logistics problem of fuel supplies. This was most critical in the area of the high density M-151 gasoline-fueled vehicle. Five HYBRID combustion systems were investigated and programs funded to provide a system which had the light-weight features of a gasoline engine and the fuel economy of a Diesel engine. This goal was essentially achieved; however, in the past ten years many new requirements for these propulsion systems have been generated which center around the ecology and the energy crisis. The Army Tank-Automotive Command is trying to satisfy all of these goals with minimum compromise.

It is for this reason that the Texaco Control Combustion System was selected for continued development in 1973. The 52-month development program will provide the U.S. Army with a family of engines which will satisfy the high-density vehicle requirements from 1/4 to 2-1/2 ton capacity. This family of engines will not only satisfy the existing emission requirements, but will also have complete multifuel capability.

Figures 131, 132 and 133 show the significant impact between emissions, fuel economy, and multifuel capability. These data are the basis for the Army's continued development of the stratified charge engine family.

Points Clarified During Question/Answer Period:

- The engine was turbo-charged to a pressure ratio of 1.2. Since this was a retrofit of an existing engine, the structure strength would not permit higher boost. The combustion system does not inherently limit supercharging or compression ratio.
- No exhaust gas recirculation was used with the turbocharged engine. The data presented are somewhat obsolete. Certainly three catalytic reactors would not be needed today to meet the standards.
- There are no problems with performance, flexibility, or low temperature starting. The engine has been started un-aided at -65 F. Acceleration capability is satisfactory to the Army.
- The engine is smoke-limited; however, no measurements have been made.

	EMISSIONS			
FUEL	HC	CO	NOx	MPG (wt)
UNLEADED GASOLINE + 2% OIL (RON-91)	.33	1.04	.61	19.80
JET FUEL (JP-4)	.26	1.09	.50	20.20
MIDDLE DISTILLATE (SPECIAL BLEND 100°F IBP-600°F EBP)	.14	.72	.59	21.31
DIESEL FUEL	.27	1.14	.60	23.03

Fig. 131 Fuel Effect on Turbocharged L-141 TCCS Emissions

FUEL*	30 MPH	40 MPH	50 MPH	60 MPH
UNLEADED GASOLINE + 2 % Oil (RON-91)	31.6	23.5	18.8	16.3
JP-4	28.0	23.6	20.6	19.4
MIDDLE DISTILLATE 100°-600°F BLEND	29.2	25.6	21.4	18.7
DIESEL	32.0	27.8	23.7	20.3

*NO CHANGE IN ENGINE CONTROL SETTINGS MADE WHEN SWITCHING FROM ONE FUEL TO ANOTHER.

**SIMULATED LEVEL ROAD FUEL ECONOMY EVALUATIONS WERE CONDUCTED ON A CHASSIS DYNAMOMETER.

Fig. 132 Fuel Effect on Turbocharged L-141 TCCS Fuel Economy**

TURBOCHARGED L-141 STRATIFIED CHARGED ENGINE

EMISSIONS AND PERFORMANCE COMPARISON WITH VARIOUS DEGREES OF EMISSION CONTROL
FUEL - GASOLINE

EMISSIONS CONTROLS	EMISSIONS GR/MI HC	CO	NOx	TRACTION POUNDS	ECONOMY MPG	PER CENT LOSS PER CONTROL	PENALTY PERCENT
BASE ENGINE	3.13	7.00	1.46	310	24.33	0	0%
8° RETARD	3.24	6.43	1.29	305	22.35	8.1%	8.1%
8° RETARD + 11% EGR	3.60	6.69	0.84	300	20.48	8.3%	15.8%
8° RETARD + 16% EGR + 2 CATALYSTS	0.22	1.29	0.66	290	19.43	5.1%	20.1%
13° RETARD + 22% EGR + 2 CATALYSTS	0.35	1.41	0.35	215	16.20	16.6%	33.4%
1976 FEDERAL STANDARD	0.41	3.40	0.40				
1975 CALIFORNIA STANDARD	0.90	9.00	2.00				

Figure 133

- The displacement of the engine is being increased to allow for growth in Army vehicle power requirements.
- The three catalysts used were noble metal oxidation catalysts.

C. Honda CVCC Vehicle Tests, by Donald Plungis, Project Engineer, Test and Evaluation Branch, EPA.

The Honda approach uses a pre-chamber into which a rich mixture of fuel and air is carbureted. This requires a second intake valve. A lean mixture is carbureted into the main combustion chamber. Combustion is initiated by a spark plug in the pre-chamber. The Honda CVCC (Compound Vortex Controlled Combustion) System is shown in Fig. 134.

Three Honda Civic Vehicles were supplied to EPA for test and evaluation in December 1972. The results are shown in Fig. 135. These results were achieved without catalysts, air injection pumps, thermal reactors or exhaust gas recirculation. It is seen that 1976 interim standards can be achieved with this vehicle.

The effects of a heavier vehicle are shown in Fig. 136. Again '76 interim standards can be achieved.

The results of more recent tests with and without EGR on the Honda vehicles are shown in Fig. 137. The '76 standards can be achieved with a penalty in fuel economy. Further comparisons of mileage are shown in Fig. 138.

Recently, tests were run in an Impala vehicle, on a Chevrolet engine modified to incorporate the CVCC combustion system. It is 350 CID, V-8 rated at 160 HP at 4000 RPM. (Stock rating is 160 HP at 3700 RPM.)

The qualitative conclusions are (Data cannot be released because the report has not yet been issued.):

- Without the use of exhaust after treatment, hardware, or ERG, 1976 interim standards were achieved. (Note exhaust manifold was large.)

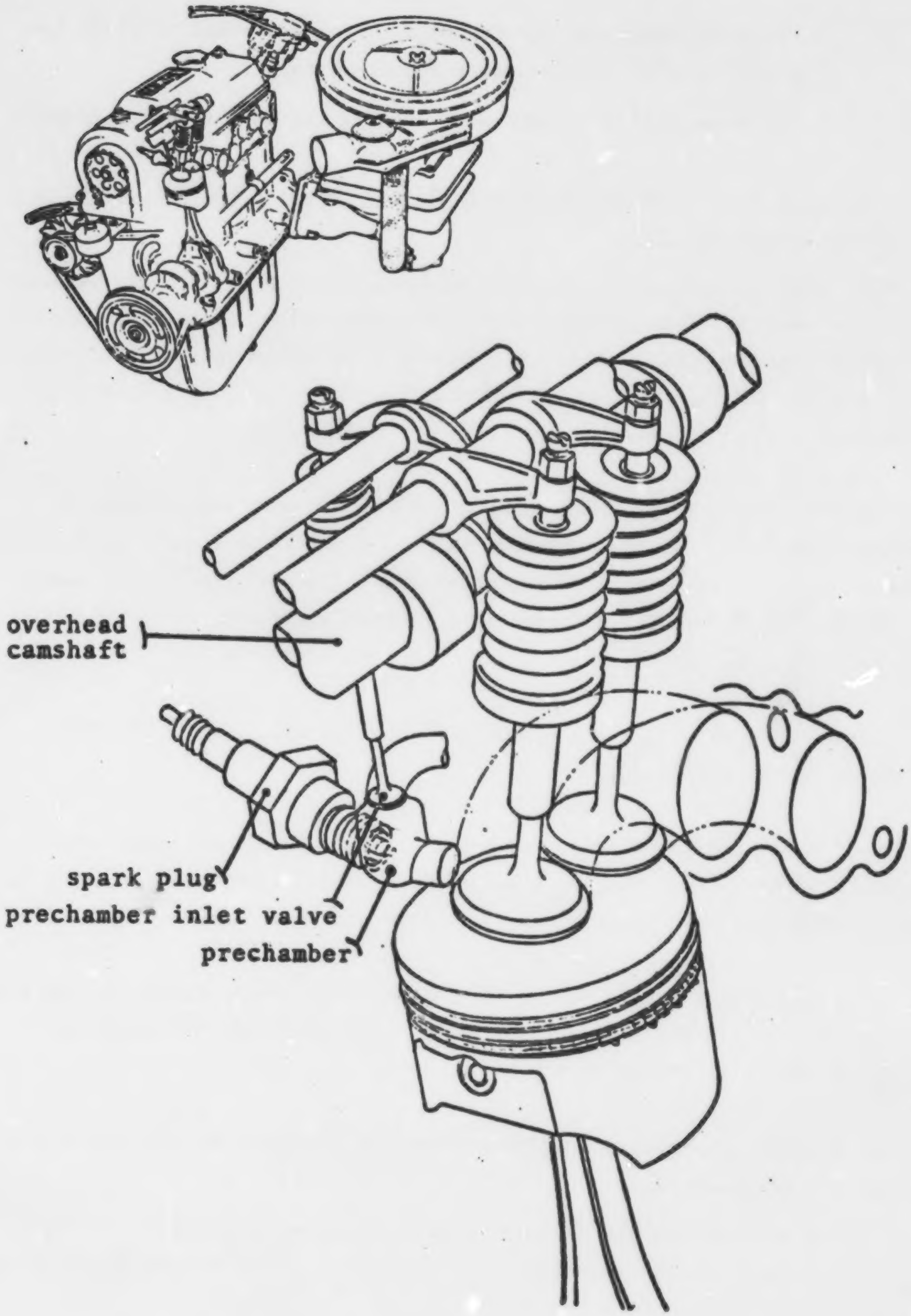
overhead camshaft
spark plug
prechamber inlet valve
prechamber

Fig. 134 Honda Civic CVCC Engine

HONDA
Civic CVCC Powered Vehicle
1975 Federal Test Procedure
(emission data in grams per mile)

	Test Number	HC	CO	NOx	'75 FTP mpg	'72 FTP mpg
Low Mileage Car #3652	16-0109	.20	2.06	.75	22.0	20.9
	16-0114	.15	1.96	.83	22.4	21.5
	16-0117	.16	2.28	1.06	21.9	20.6
	16-0118	.21	2.24	.86	22.1	20.9
	16-0122	.19	2.05	.94	22.1	20.9
	AVERAGE	.18	2.12	.89	22.1	21.0
50,000 Mile Car #2034	16-0106	.19	1.73	.65	21.1	20.0
	16-0110	.25	1.73	.57	22.2	19.7
	16-0115	.26	1.70	.64	21.0	19.8
	16-0116	.26	1.85	.73	20.8	19.5
	AVERAGE	.24	1.75	.65	21.3	19.8
Low Mileage Back-up Car #3606	16-0123	.23	2.00	1.03	20.7	19.5
1975 Federal Standards		.41	3.40	3.1		
1976 Federal Standards		.41	3.40	.40		

Above tests run @ 2000lbs. inertia and 8.3 rear wheel hp @ 50MPH

Figure 135

	Ave. EPA test @ 2000 lbs.	Test @ 3000 lbs.	'76 Std.
HC (gm/mi)	0.21	0.28	0.41
CO (gm/mi)	1.96	3.08	3.40
NO_x (gm/mi)	0.87	1.56	0.40
Fuel Eco. (MPG)	21.6	19.4	--

Fig. 136 Effect of Inertia on 119 CID CVCC-Powered Civic — 1975 FTP Emission Results

		-EPA Results-	-Recent Honda Test Results-	
	'76 Std	Avg. Result 12/72 Test'g	Avg. 6 tests w/o EGR	Avg. 10 test with EGR
Hydrocarbons (gm/mi)	0.41	0.21	0.24	0.29
Carbon Monoxide (gm/mi)	3.4	1.96	1.91	2.71
Oxides of Nitrogen (gm/mi)	0.40	0.81	0.47	0.26
Fuel Economy (gm/mi)	--	21.6	20.5	18.1

Vehicles tested at 2000 lbs. inertia

Fig. 137 Recent 1975 FTP Results of Tests on 119 CID CVCC-Powered Civic

*Avg. 1973 vehicle fuel economy for 2000 lb. vehicles	25.5 mpg
1973 Civic 4000-mile certification data (71 CID engine)	23.6 mpg
Avg. fuel economy for 119 CID CVCC Civic tested at 2000 lbs.	20.3 mpg
*Avg. 1973 vehicle fuel economy for 3000 lb. vehicles	16.2 mpg
Fuel economy for 119 CID CVCC Civic tested at 3000 lbs.	18.7 mpg
Avg. fuel economy for 119 CID CVCC Civic tested at 2000 lbs. with EGR	17.9 mpg

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* EPA Certification Tests

Fig. 138 1972 FTP Fuel Economy Comparison — 119 CID CVCC-Powered Civic

- Fuel economy was equivalent to 1973 vehicles (about 10 mpg for 5000 lb vehicle) of similar weight and displacement.
- Cold start, drive-away and cold-start emissions were very good.

Points Clarified During Question/Answer Period:

- With such lean mixtures in the main chamber and with some wall quenching, it is surprising that such low HC levels can be achieved. Exhaust temperatures are high; there must also be a lot of turbulence.
- It was suggested that a more rational comparison criterion for vehicle fuel economy might be ton-miles per gallon or seat-miles per gallon.
- Although not measured specifically, it is suspected that high under-hood temperatures might constitute a problem.

D. Volkswagen Program, by Professor Heitland, Volkswagen, Wolfsburg, Germany

The principal aim initially was to reduce NO_x, however, recent trends in requirements make it important to also reduce UHC and CO to avoid any significant reduction in the engine's specific power output. A large number of tests were conducted on a single cylinder engine with different combustion chamber configurations, and on a four-cylinder engine under steady state and transient conditions in the laboratory and in vehicles.

In view of the large number of parameters to be investigated, the main parameters were studied by computer simulation techniques and by basic combustion bomb experiments. The mathematical flow model enabled the simulation of processes taking place in the cylinder and prechamber, including thermodynamic cycle calculations and the cylinder charging process.

The mixture formation phase and subsequent combustion were studied in the bomb using high-speed photography, shadowgraph, and Schlieren techniques.

Figure 139 shows the measured HC and NO concentrations related to mean effec-

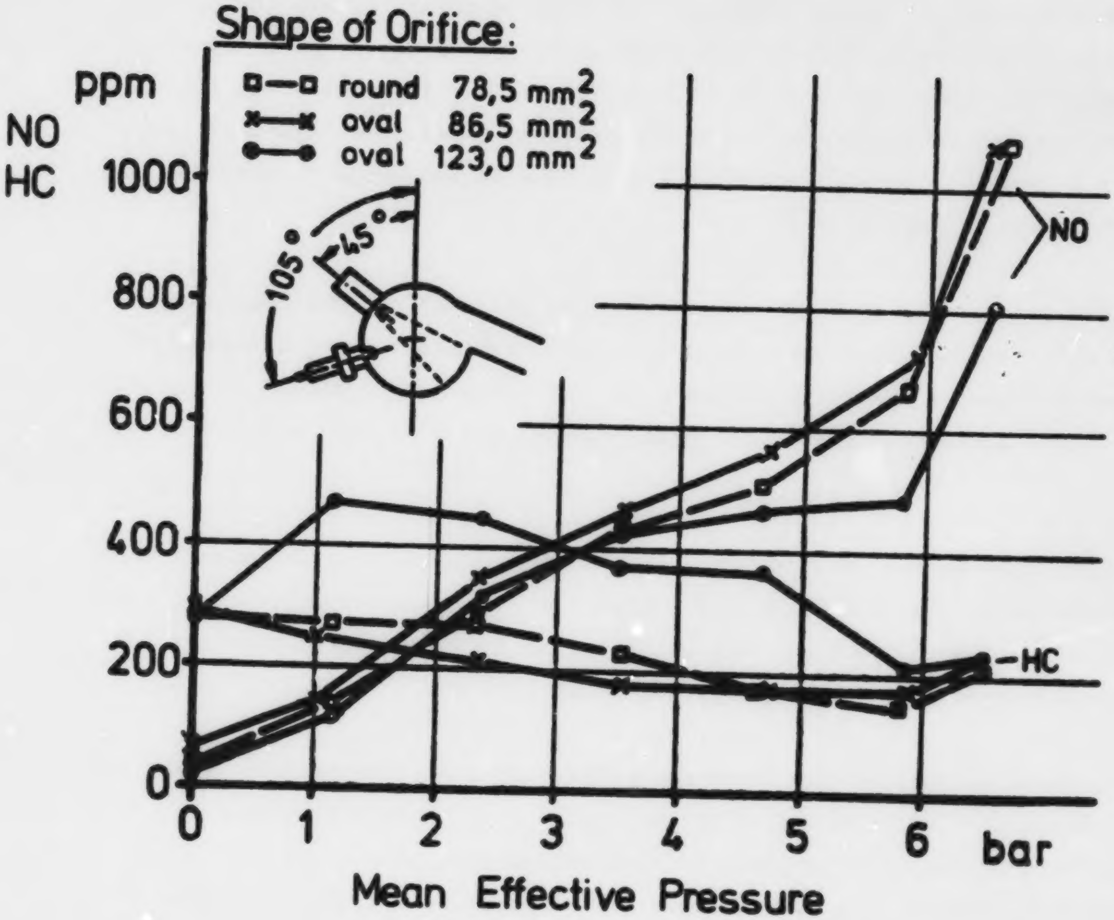


Fig. 139 Influence of Transfer Passage Geometry on Emissions (Unthrottled, 2000 RPM)

tive pressure with a specific injector and spark plug position, and using various transfer flow passages. Whereas the NO concentrations in the lower load range varied only slightly among themselves, a distinct advantage was noted in favor of the larger cross section passage at mean effective pressures above 4 bars. At low mean effective pressures the HC concentrations are widely scattered since combustion chamber temperatures are low and the quality of mixture formation is not satisfactory. However, with regard to HC emissions the larger passage is less favorable. Injectors with low delivery pressures provided the best test results of all the injectors investigated, probably on account of avoidance to a large degree of gasoline deposit on the prechamber wall.

Figures 140 and 141 show pollutant emissions and fuel consumption versus mean effective pressure with the operating parameters showing the effects of the portion of fuel injected into the prechamber and ignition timing. All values apply to unthrottled intake condition and an engine speed of 2000 rpm.

Further improvements, particularly in the lower engine load range, can be obtained by intake air throttling. Figure 142 shows the dependence of specific fuel consumption and exhaust emissions on the degree of throttling for three different mean effective pressures at 2000 rpm.

Although no noticeable influence was evident on fuel consumption, intake air throttling is advantageous at low engine load because it produces a clear drop in emission levels. At high engine load, excessive throttling leads to a renewed rise in emissions. From about half load, the engine can be operated without throttling.

Based on the results of tests conducted with the single-cylinder engine using different combustion chamber configurations, and the investigation of influences of various operating parameters, an air cooled 1600 cm^3 engine was produced. A feasible concept had been shown to the public in May, 1972, at the United States International Transportation Exposition

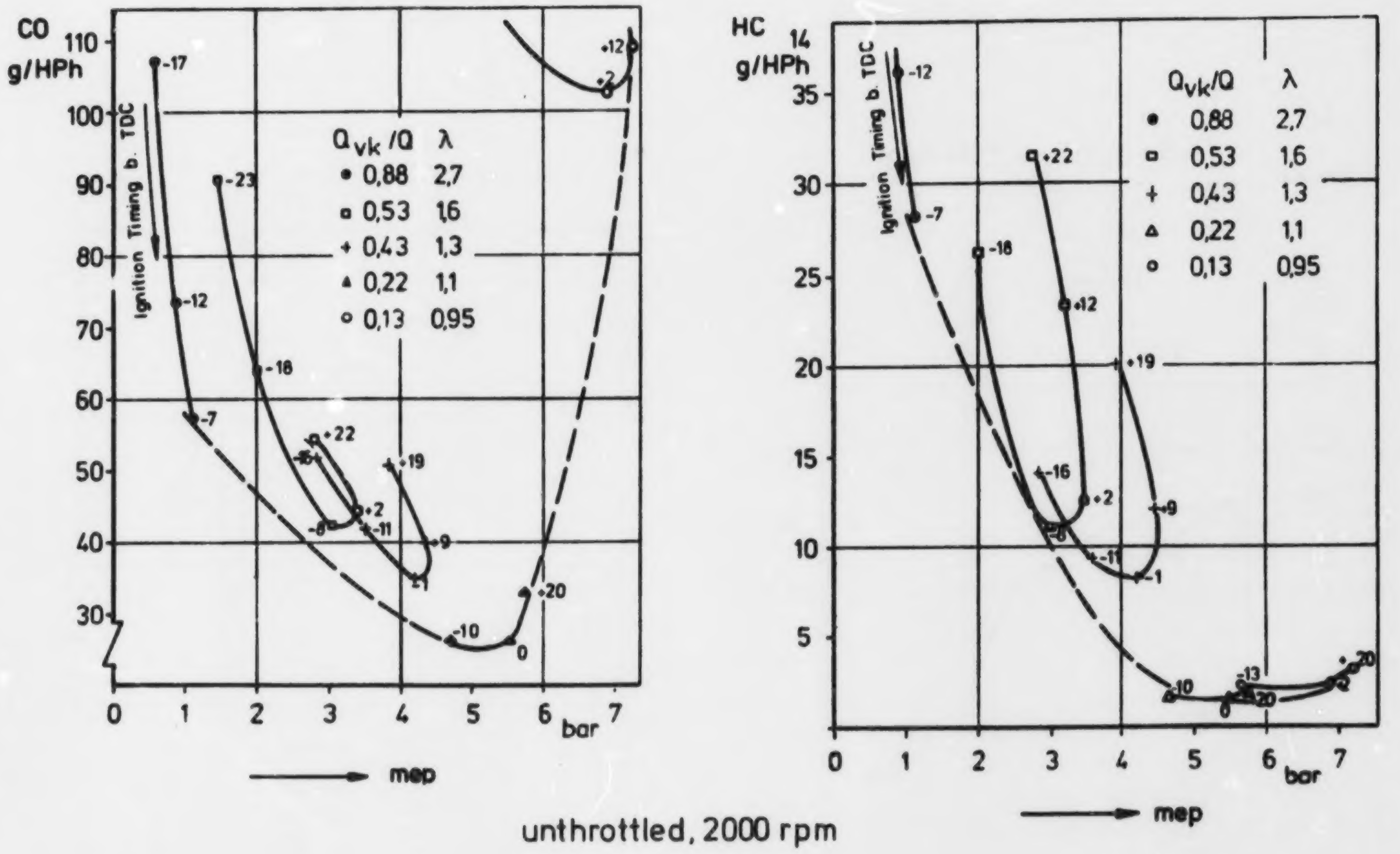


Fig. 140 Influence of Fuel Distribution, Q_{VK}/Q, and Ignition Timing

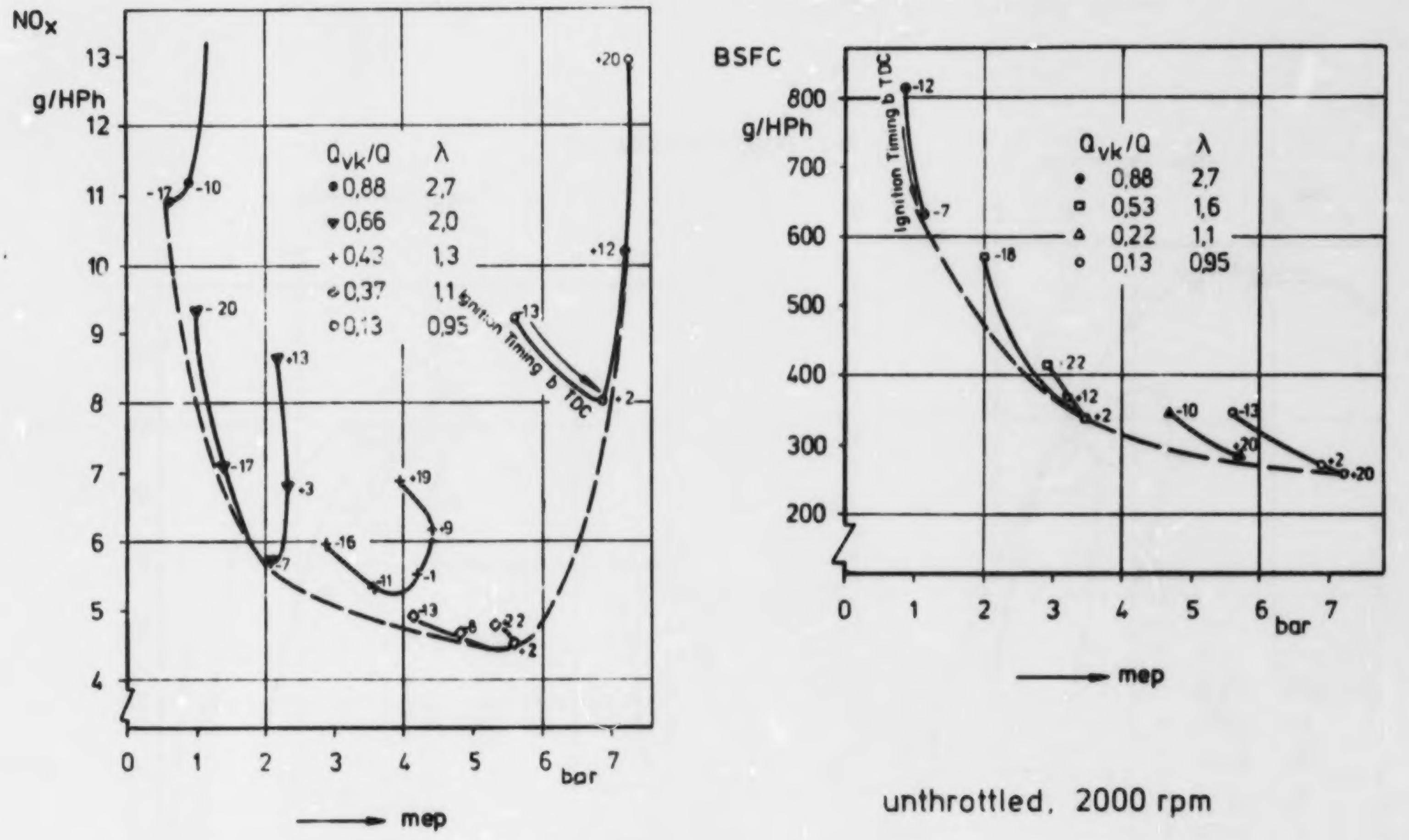


Fig. 141 Influence of Fuel Distribution, Q_{VK}/Q, and Ignition Timing

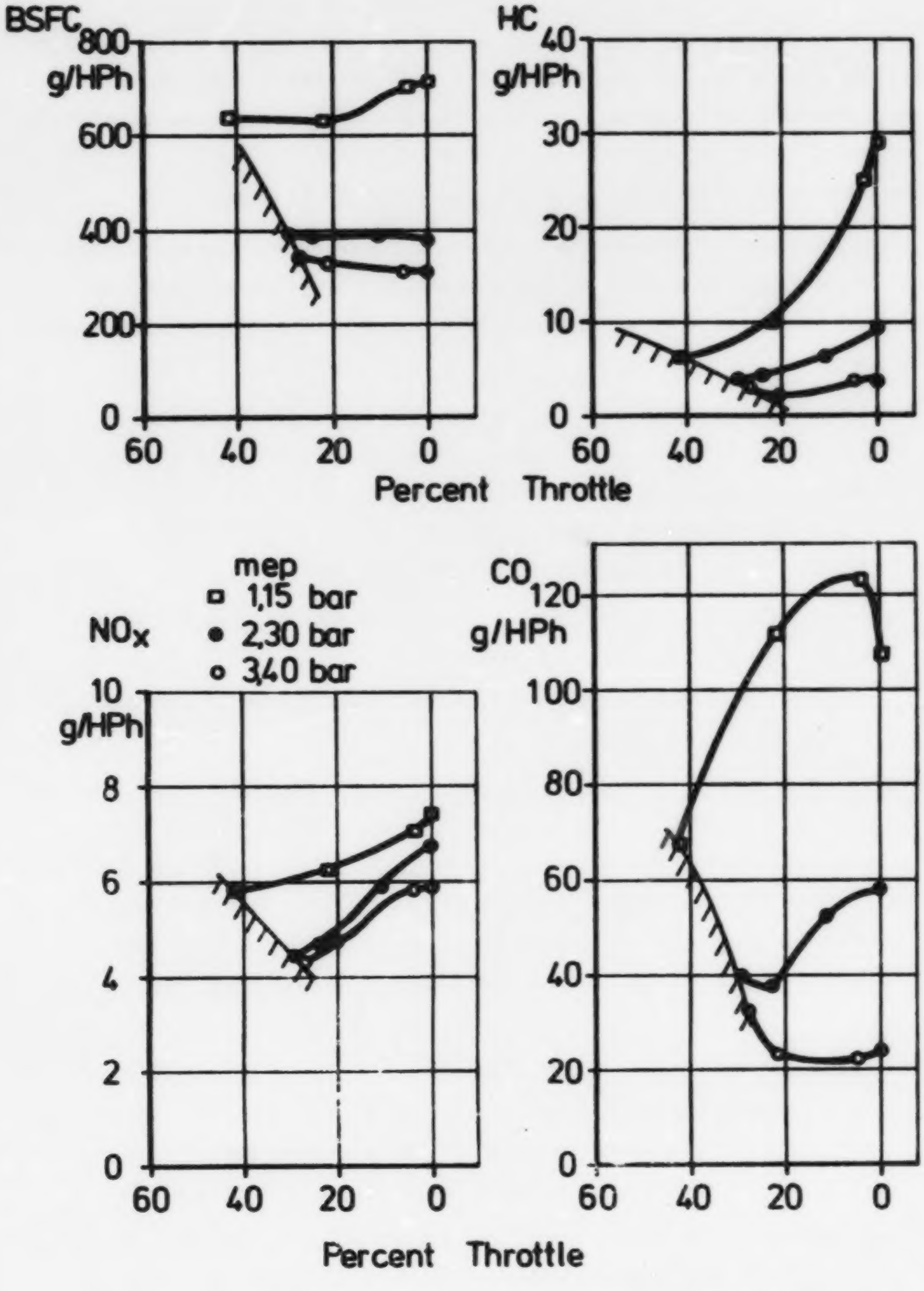


Fig. 142 Influence of Intake Air Throttling

(TRANSPO -72) in Washington (Fig. 143). A conventional four-plunger gasoline injection pump was initially used for direct fuel injection into the prechamber with an auxiliary carburetor for preparation of the secondary mixture.

The present status of the program may be summarized as follows:

- Investigation of various combustion chamber configurations has shown that from the emissions point of view, the divided combustion chamber comprising a main and a prechamber is advantageous.
- Stratified charge in a divided combustion chamber enabled a considerable drop in NO_x emissions whereas reduction of the HC emissions is a more difficult matter. However, in the case of the multi-cylinder engine conditions for thermal oxidation in the exhaust system are favorable.
- Acceptable emissions with a minimum power loss can only be obtained by accurate control of the fuel quantities supplied to the main and prechamber, and by throttling of the intake air in the part load range.
- Equipped with a specially designed compact fuel-injection pump the air cooled PCI (Pre Chamber Injection) stratified charge engine is being tested in the Volkswagen Beetle. Results in respect to performance, economy, driveability, and emissions are encouraging. The system is being converted for the water cooled engine of the recently introduced Passat Model VW.

Points Clarified During Question/Answer Period:

- In the first car with a PCI engine installed, the power level reached 48 HP compared to 50 HP of the standard Beetle. Power is limited by heat sensitivity, not combustion limitations.
- Although only a little work has been done so far at cold start conditions, the engine is surprisingly good under this mode of operation.

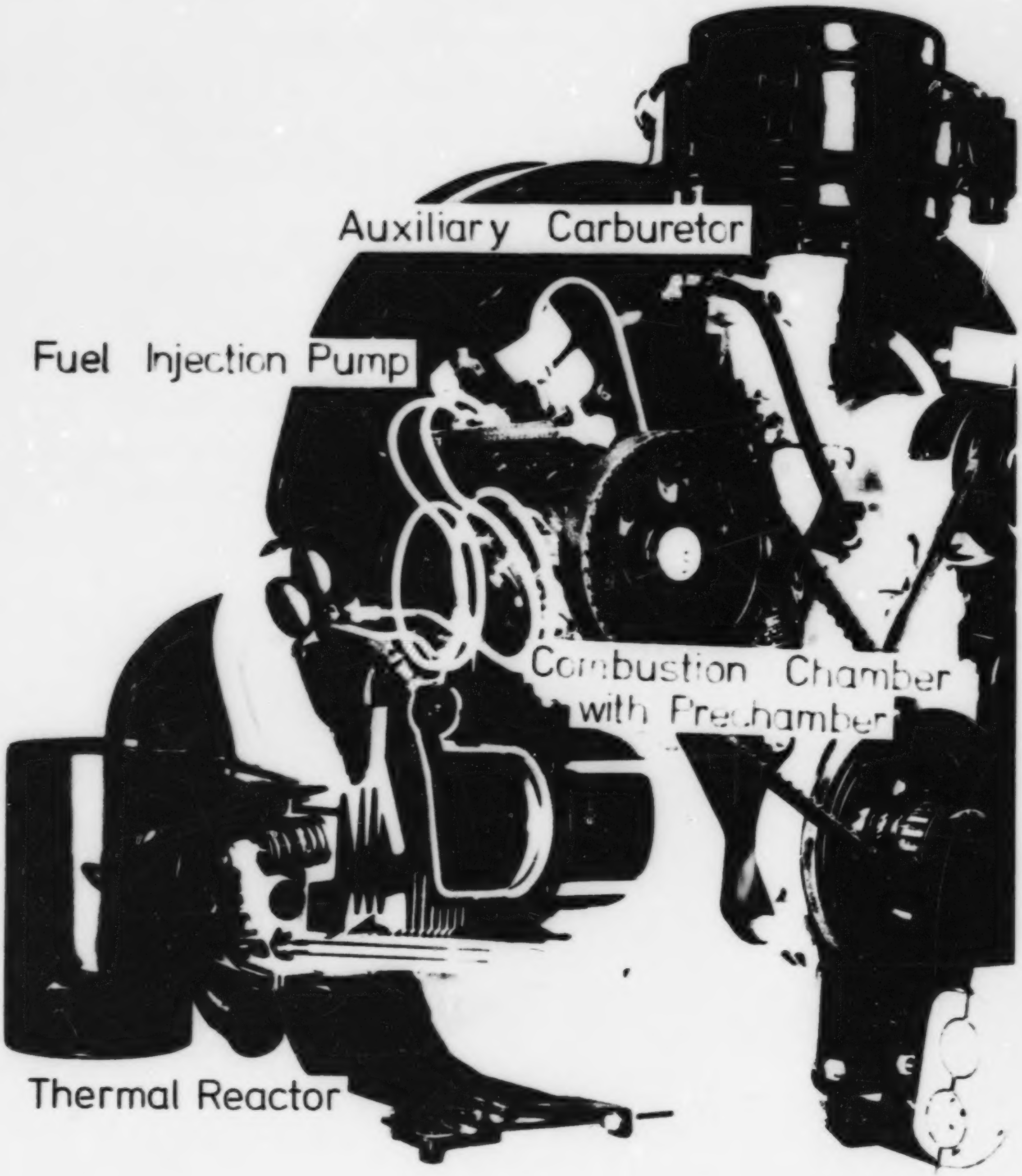

Auxiliary Carburetor
Fuel Injection Pump
Combustion Chamber with Prechamber
Thermal Reactor

Fig. 143 1600 ccm VW PCI-Engine

- There are some problems in the throat area of the pre-chamber; however, overall heat losses do not seem to have changed appreciably. Heat rejection has not been looked at specifically.
- The analytical studies reduced the amount of experimental work necessary to determine the optimum ratio of fuel injected into the pre-chamber to that injected into the main chamber.
- The low pressure injection is about 20 psi.
- Tests were on a bare engine (no inlet air cleaner or exhaust muffler).
- Throttling was used only at part load; full load was with wide open throttle. BMEP's at full load were about 100 psi.
- At idle and light load all of the fuel is supplied to the pre-chamber; at full load about 10% of the fuel is supplied to the pre-chamber.

VI. DIESEL ENGINES FOR LOW POLLUTION FROM AUTOMOBILES

A. Presentation by Diarmuid Downs, Managing Director, Ricardo & Co. Engineers, Ltd., Shoreham-by-Sea, Sussex, England

By the outbreak of the last War, the Diesel engine had already become almost universal in Europe for city buses and for the larger commercial vehicles. In the post-War period, use of the Diesel engine has spread downwards in size to smaller commercial vehicles, delivery vans, agricultural tractors, taxi-cabs, and private cars. The principal incentive for the adoption of the Diesel engine was its good fuel economy compared with that of the gasoline engine.

The Dieselization of road transport has proceeded much less rapidly in the United States than in Europe, mainly because the fuel costs were lower, in part due to a small tax component in the total fuel price. Now that fuel prices have risen in the United States and show signs of climbing even higher, it is logical to expect increased use of the Diesel engine in small commercial vehicles which presently use gasoline engines. Some 2 1/2 million such vehicles are produced every year. Attention here is focused on the Diesel engine for American automobiles, mainly on pollution grounds, but also having advantages in energy conservation.

Although a number of Diesel engine models are made and marketed, even in Europe the percentage of automobiles powered by Diesel engines is small. This is mainly due to higher first cost, lower power-weight ratio, and noise (particularly at idle) compared with the gasoline-engined vehicle although improvements have been and are continuing to be made in all these respects. In some countries in Europe the tax on Diesel fuel is lower than on gasoline, but in others, such as England, it is the same and so a case must be made for the Diesel engine not on the grounds of cheaper fuel but better economy alone.

The fuel consumption of the Diesel engine compared with that of the gasoline engine is more favorable the lower the load and the lower the speed, and is most favorable at idle. The fuel saving to be obtained depends very much on the duty cycle of the automobile. Under motorway operating conditions, the savings may be no more than 5%, on mixed driving on English roads it is generally about 30%, and in city taxi service it can approach 50%. All of London's taxi-cabs are now Diesel-powered and the mileage obtained per gallon of fuel is almost double that of the gasoline engine it superseded.

Although the case for Diesel-engined automobiles in Europe is made on economic rather than environmental grounds, the current interest in air pollution, particularly in the United States, has prompted measurements and studies of exhaust emissions from these vehicles. All the European Diesel-powered automobiles we have tested have given closely similar figures for the 1975 U.S. Federal Test Procedure (1/6 g/mile for CO and 1.2 g/mile for NO_x). The HC figures are more varied and the best we have recorded is 0.17 g/mile. These figures are well below those proposed by the U.S. Federal authorities for 1976 and would probably satisfy an NO_x requirement of 1.5 g/mile should this be the minimum figure chosen by the Government for 1977.

These figures are for standard production Diesel-engined passenger cars. If the Government decides on a lower limit for NO_x than 1.5 g/mile for 1977, such as the 0.4 g/mile originally proposed for 1976, what potential is there for reduction of NO_x by attention to the detailed design and operation of the engine? All of these engines have either swirl chamber or pre-chamber combustion systems. These are the only ones which will give the good air utilization over a wide speed range combined with low exhaust smoke and acceptable noise level in the small cylinder size required for European automobile Diesels. These same combustion systems are also favorable as compared with direct injection from the point of view of nitrogen oxide emissions. No further gain can be expected, therefore, from changes to the combustion chamber design, although this is not to say that basic minor modifications might not be beneficial. Test work has shown however, that retarding the injection timing and optimizing it over the load and speed range can reduce nitrogen oxide emissions. From these test results, it is estimated that the nitrogen oxide emissions from a vehicle could be reduced to 0.7 g/mile, leaving the CO and HC unchanged. The noise level of the engine would also be reduced. Some trade off (perhaps 10 - 12%) in specific power output and fuel economy can be expected. Still further reduction in nitrogen oxide emissions, to perhaps just below 0.4 g/mile could be obtained by exhaust gas recirculation.

A Diesel-Engined Automobile for America: The typical European car considered so far weighed 2800 lb and had a 65 hp Diesel engine. A standard American car weighing some 4500 lb would require a larger and somewhat heavier engine to give the vehicle performance the customer would expect. Although the trend to smaller cars would seem likely to continue in the United States, a vehicle weighing perhaps 3200 lb with a Diesel engine will probably have the greatest interest. An engine of about 73 hp would be required for the same power/weight ratio as the European car. Based on the figures for the European car, the emissions per mile might be expected to increase roughly as the weight of the vehicle to:

HC 0.19 g/mile, CO 1.8 g/mile, NO_x 1.4 g/mile.

Such an engine would have only just sufficient horse power to drive the Federal Test Cycle. A somewhat larger engine would be required to cope with American traffic conditions.

Two examples (a) a 6 cylinder unit of 100 hp and (b) a V-8 unit of 130 hp are considered here. These engines would be driven at the same power but at a lower load factor over the test cycle than the 73 hp engine. In the indirect injection Diesel engine the specific emissions of HC and NO_x on the basis of g/bhp-hr increase as the load is reduced. Hence, the larger engines will give higher mass emissions/mile for the same power plant output than will the small engine. However, the CO should be about the same. The estimated emission figures for these two examples are shown in Fig. 144. It can be seen that with either engine the 1.5 g/mile NO_x limit could not be satisfied, but that even with the 130 hp engine a 2.0 g/mile limit could probably be met. The HC and CO figures would be satisfactory in both cases.

A 3200 lb AMERICAN CAR WITH DIESEL ENGINE

Estimated Emissions According to US Federal 1975 Procedure

	g/mile		
Engine	HC	CO	NO_x
73 hp	0.19	1.8	1.4
100 hp	0.24	1.8	1.6
130 hp	0.33	1.8	1.9

Figure 144

This would be a standard Diesel engine but, as in the European example, reductions in NO_x emissions could be obtained by optimizing the injection timing over the load and speed range to bring the level to perhaps 1.0 g/mile in the case of the 100 hp engine and 1.3 g/mile in the case of the 130 hp engine. Both are within the 1.5 g/mile limit. Still further reductions could be obtained by the use of exhaust gas recirculation. Turbocharging would also have advantages so far as NO_x is concerned as in this case, specific NO_x emissions increase less steeply as the load is reduced. The CO should also be slightly lower, with HC probably unchanged.

A Diesel Engine Designed for an American Automobile: For the larger engine of 130 hp, a unit of 289 cu. in. capacity would be required with a speed range, 1000 to 4000 rpm. To avoid having a long engine in the interest of vehicle design for safety, a V-8 configuration with a bore of 3.45 in. and a stroke of 3.85 in. would have advantages. A swirl chamber combustion system would be used to give good power output over a wide speed range, combined with low exhaust emissions.

Two important factors to be considered when converting to a Diesel are the increased engine weight and cost. The engine under consideration in cast iron would weigh about 700 lb compared with 475 lb for the equivalent gasoline engine. An aluminium Diesel would reduce the differential to about 85 lb. The cost of manufacture of the Diesel engine would be about 40% higher than the gasoline engine and in large scale production the aluminium engine might cost a similar amount. Thus the effect on vehicle cost should only be about 5%.

It should be pointed out that the price differentials between gasoline and Diesel cars in Europe bear little relation to the cost of production, but are based on estimates of what the current market will bear. Thus, one Diesel car marketed in England cost $1100 more than the gasoline-engined car, or an increase of 15% in the total price.

Such an engine would enable a vehicle to be produced having a performance comparable with that of current American automobiles. However, it may be that on energy conservation grounds, a lower performance will increasingly become the norm, in which case 100 hp might suffice. For a lower power a six-cylinder unit would probably be chosen with a 3.55 in. bore and 3.44 in. stroke, and a capacity of 204 cu. ins., rated at 100 hp and 4000 rpm.

Points Clarified During Question/Answer Period:

- Turbocharging makes more sense for the larger American automobiles than for the small European vehicles.
- A potential problem of high wear rates might come up with EGR systems since Diesel engines often have particulates in the exhaust.

B. Presentation by George Donald, Superintending Engineer, Vehicle Engineering Division, Department of Environment, London, England

An investigation has been made into the relative pollution levels produced by Diesel engines in Great Britain in comparison with gasoline and gas turbine power units. The results show that the Diesel is indeed a low pollution engine in its current form. There are many areas in which improvements can be made on all three types of engine, but it is quite clear that the Diesel has a long lead already.

Combined HC and NO_x emission levels measured to the USA Federal 13 Mode Cycle on typical British direct injection Diesels show that in their current form these engines just meet the 1973 requirements. Methods whereby improvements can be made include turbocharging and intercooling; retarded fuel injection timing; increased rate of fuel injection; reduced nozzle sac volume; pilot injection; water injection and exhaust gas recirculation.

Work on indirect injection engines has shown that certain types emit much lower NO_x levels than direct injection types when tested to the 13 Mode Cycle. These IDI engines already have combined $HC+NO_x$ levels relatively close to the 5 gm/bhp/hr level required by the 1975 Federal USA proposals. It is possible that the changes to direct injection engines necessary for them to achieve the 1975 level may increase their specific fuel consumption sufficiently to eradicate their higher thermal efficiency relative to IDI units.

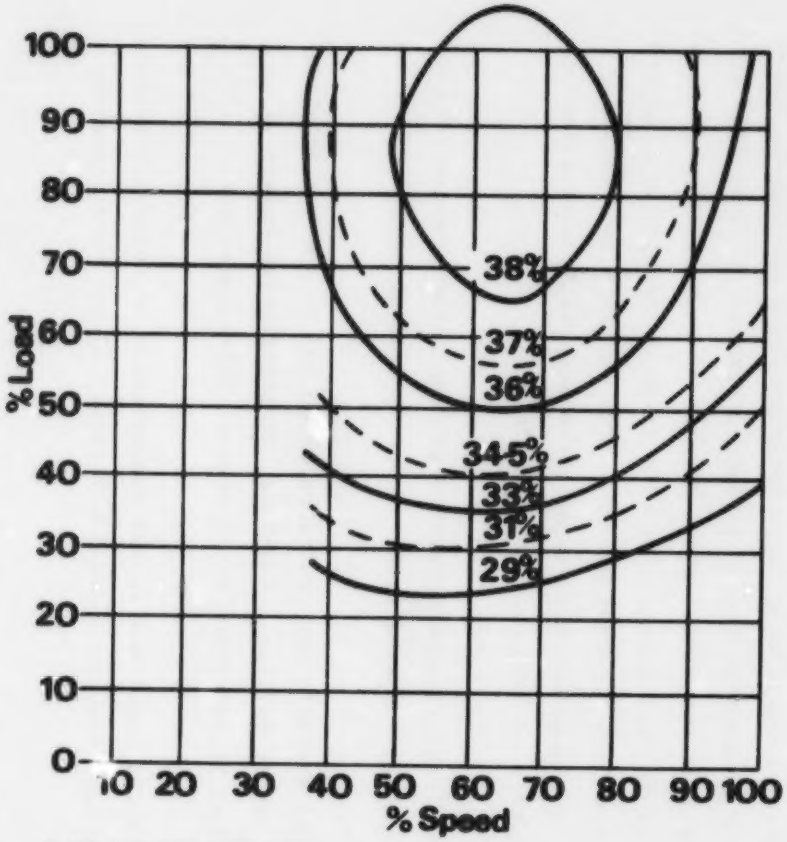
The British direct injection engine CO emissions are only a small fraction (20%) of the 1975 level and it is evident that this does not present a problem in the foreseeable future. Careful consideration has been given to the topographical and climatic conditions in Great Britain in relation to their effect on the formation of smog. It has been found that the characteristic conditions in Los Angeles whereby NO_x and oxygen interact to form smog do not exist in Great Britain or only occur very exceptionally. Hence, it is evident that priorities in California must, of necessity, be different.

Based on these considerations, Great Britain has confined its Diesel emission legislation to the control of smoke levels. Public adverse reaction to Diesel engines has been restricted almost exclusively to the emission of visible exhaust smoke. The critical conditions occur when relatively slow moving diesel powered trucks are ascending lengthy grades, particularly if narrow winding roads prevent such vehicles being overtaken. Under these conditions, the automobile driver becomes increasingly frustrated and any inability to see past the Diesel truck because of exhaust smoke obscuration greatly adds to his annoyance and results in major criticisms. Accordingly, legislation has been directed against smoke emission and the standards which engine manufacturers have to meet are materially more severe than those now permitted or even projected in the USA.

There has been some slight adverse comment regarding Diesel exhaust odor, but this is infinitesimal compared with the outcry against smoke.

In view of the Diesel engine's low emissions of CO and HC and the relative unimportance of NO_x under British conditions, no legislation exists or is envisaged for the near future which would control these emissions.

The Diesel engine can be important to the conservation of natural resources. Figures 145 and 146 show how the thermal efficiency of the Diesel engine



DOE VE DIV OCT 1973

Fig. 145 Map of Direct Injection Diesel Engine Thermal Efficiency

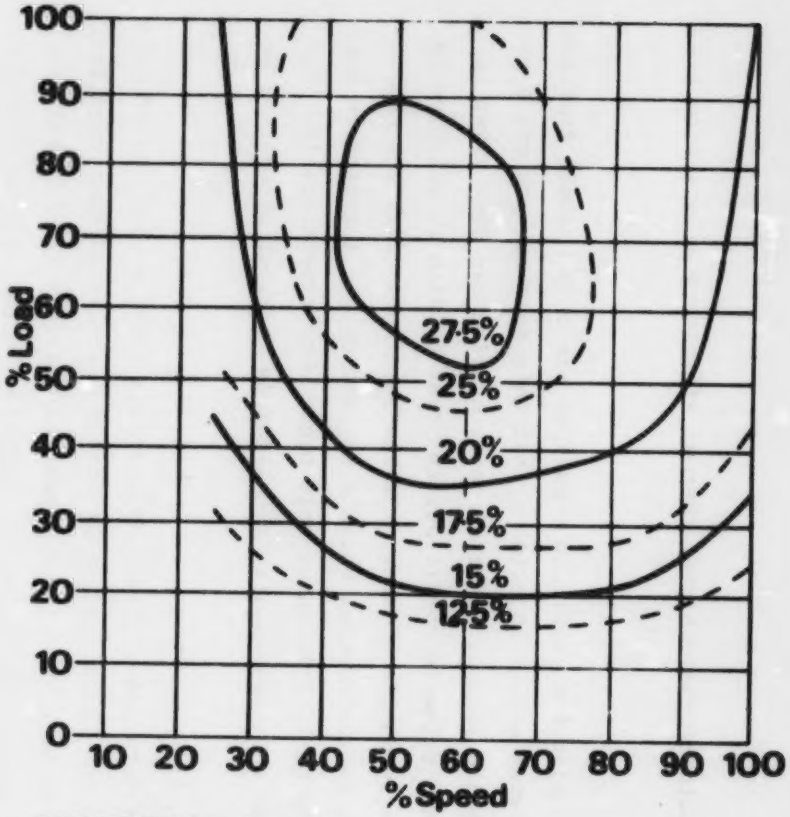


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Fig. 146 Map of Gasoline Engine Thermal Efficiency

compares with that of the gasoline engine over the load and speed ranges. Attention is drawn to the very good thermal efficiency shown, and in particular the spread of speed and load (from 48% to 79% and 62% to 104%, respectively) over which a thermal efficiency of 38% or better is achieved by the Diesel engine. In addition, the excellent part load thermal efficiency is apparent which is responsible for the very good overall road fuel consumption achieved by this type of power unit.

Figure 146 gives the same data for a gasoline engine. The optimum thermal efficiency of only 27.5% - 10 1/2% worse than for the Diesel - is only achieved over a speed range of 41% to 66% and a load range of 52% and 89%. This spread compares unfavorably with the Diesel engine and emphasizes still further the relatively poor efficiency of the gasoline unit. As the load is decreased, the gasoline thermal efficiency falls off rapidly, and at about 20% load it is only half that of the Diesel unit.

Another way in which the Diesel engine contributes to the efficient use of natural resources involves the manufacture of the fuel. In the process of producing end products from crude oil, the various fractions are drawn off at different levels of the fractionating column. The automotive Diesel uses a "cut" which is different from that of both gasoline and heavy fuel oil and thus helps to use the crude oil more effectively. Furthermore, it is possible to operate Diesel engines on a much wider variety of fuel than can be digested by gasoline engines. This includes gasoline, aircraft and other turbine fuels, and kerosine.

Yet another advantage of the Diesel engine is its greatly reduced fire hazard. The inflammability of Diesel fuel oil is very much less than that of gasoline and of some turbine fuels.

Comparative emission tests were carried out on gasoline and Diesel engined vehicles to ECE Regulation 15, Type I Test. This involves the use of a vehicle which has run at least 3000 kilometers. It is subjected to a "soak" period of at least six hours at a temperature of between 20° and

30°C. The engine is then started from cold and allowed to idle for 40 seconds after which the test is commenced. The latter comprises a 15 mode cycle including idling, acceleration, steady speed and deceleration which is closely controlled and simulates urban European driving conditions. This cycle is carried out 4 times without interruption, giving a total test duration of 13 minutes. Thus the engine passes through the majority of the warming up phase during the test. The emissions from the Diesel engine were in all cases considerably less than those from the gasoline unit. Hydrocarbon Diesel emissions were only 5.8%; carbon monoxide 16.9% and oxides of nitrogen 58% of the gasoline quantities.

Similar comparison was carried out to the USA 1972 Federal requirements for light duty gasoline engines. Exhaust emissions were analysed by the CVS method. The grams/mile emissions from the USA cycle are much higher as regards CO, being over three times as much. The NO_x rate is slightly more and the HC level somewhat less than the ECE figures. The USA test gave HC Diesel emissions 8% of the gasoline figures and the NO_x level of 52.7% of that produced by the gasoline engine.

Public disquiet over the emission of visible smoke resulted in the evolution of a British Standard in 1967 and this was developed further to become BSAU141(a)1971. The latter is tied to our Construction and Use Regulation. Type approval of engines to this standard has been a legal requirement since 1 April 1973.

The British Standard requirement is far more severe than the USA lugging mode level even for 1974. The British smoke level must not be exceeded over the full load speed range from the maximum power rated speed down to 45% of this speed or 1000 rpm, whichever is the higher; whereas the USA lugging mode test only comes down to the maximum torque or to 60% of rated speed, whichever is higher. This represents a further easing of the smoke emission requirements relative to the UK standard.

Points Clarified During Question/Answer Period:

- Diesel engine noise is a key problem which is receiving a lot of effort.
- No quantitative data on particulates were presented; both visible and subvisible sizes are considered important.
- It was suggested that a reduction in Diesel fuel prices would encourage more people to use these engines.
- Odor is a serious Diesel problem, work on this subject is in progress in the U.K..

C. EPA Diesel Study Status, by John J. McFadden, Emission Control Technology Division

A technical feasibility study and evaluation assessment was carried out on four light duty vehicles powered by Diesel engines to establish the potential of Diesel engines for low exhaust emissions. Tests were conducted in accordance with 1975 Federal Test Procedures for Light Duty Passenger Vehicles. The results are shown in Fig. 147. An inherent low emission capability suitable to meet 1975 Statutory Standards was demonstrated by all vehicles except the Peugeot, which had a special deferred injection timing to reduce idle noise. Average fuel economy exceeded that of standard vehicles in the 3000 - 3500 lb weight category (23.6 - 25.2 mpg as compared to 14 - 16 mpg).

Questions have been raised about whether or not the gaseous emissions from a Diesel engine are significantly different from those of gasoline engines and if these effluents have different health effects. Also, will the noise, smoke, and odor of Diesel engines create or contribute to a public nuisance? To resolve these questions, two programs have been initiated.

Southwest Research Institute has been contracted to characterize the emissions from available Diesel cars and quantify the data to better assess the potential of this inherently low emission engine. The four main tasks involve characterization of gaseous, smoke, odor and noise emissions. Also

Vehicle	No. Tests	Inertia Weight	Transmission	HC (gm/mi)	CO (gm/mi)	NO_2 (gm/mi)	Fuel Economy (MPG)
Mercedes 220D	5	3500#	4 speed auto	0.34	1.42	1.43	23.6
Mercedes 220D (modified)	5	3500#	4 speed auto	0.28	1.08	1.48	24.6
Opel Rekord 2100D	5	3000#	3 speed auto	0.40	1.16	1.34	23.8
Peugeot 504D	5	3000#	4 speed manual	3.11	3.42	1.07	25.2
Datsun-Nissan 220C	2	3500#	4 speed manual	0.21	1.69	1.72	24.0
			'75 Statutory	0.41	3.4	3.1	--
			'75 Interim	1.5	15	3.1	--
			'75 California	0.9	9	2.0	--
			'76 Statutory			0.4	

All Vehicles Were: 4-Door, 4-Cyclinder, Indirect Injection, 2.1-2.2 Liters.

Fig. 147 Mass Emissions and Fuel Economy from LDV Diesel Engines — 1975 FTP

tests are to be run on a stratified charge gasoline engine and an advanced emission controlled light duty gasoline engine.

The second contract calls for an objective study of the problem areas associated with the Diesel engine to determine the impact of a large number of Diesel passenger cars on both manufacturers and consumers. Ricardo is to conduct this study. It will include:

- Literature search
- Problem area trade-off methodology and analysis
- Engine configuration study
- Recommendations for further research

EPA also plans to test a Comprex supercharged Mercedes 220D Diesel engine in mid 1974. It offers possibilities for better control of HC, NO_x, and CO emissions.

Points Clarified During Question/Answer Period:

- It was suggested that EPA make a fuel availability study.
- Sulfate emissions may be a problem with high sulfur Diesel fuels. Such tests have recently been included in the EPA testing.
- It was suggested that the acceleration response of some Diesel cars is sluggish. With a response comparable to gasoline cars, the Diesel car might have different fuel economy and emissions.
- Operating costs of Diesel engines are included in the above studies.

VII. ROTARY COMBUSTION ENGINES

A. General Status of the Wankel Rotary Engine, by Professor D. E. Cole, University of Michigan

The future of the Wankel rotary combustion engine is shrouded in secrecy as numerous technical groups study its potential. The lack of public discussion is a measure of the serious consideration being given to this engine as an alternative to the conventional piston engine. Unfortunately, even some of the research at the University of Michigan is proprietary, thus preventing public disclosure of results.

The major advantages of the rotary combustion engine are its small size and light weight. These features enhance its packaging flexibility and provide the designer with another tool to reduce vehicle weight. Other important advantages include:

- simplicity
- fewer components
- better breathing
- broad speed range
- low friction
- no special fuel requirements
- perfect balance

The most promising application of the engine appears to be in the intermediate and full-size vehicle rather than the compact car. Use of the rotary combustion engine with an integrated drive train could result in a weight saving of 20-25% in the large American car. A transversely mounted front engine, front drive system appears to be the most attractive package.

For example, the current 4000 lb car could be reduced in weight by as much as 1000 lbs with no sacrifice in interior volume. Commensurate with this exterior size and total weight reduction would be improvements in fuel economy, exhaust emissions, and performance per installed horsepower.

Several development problems remain and are evident in some current mass produced rotary engines. Perhaps the most significant is poor fuel economy. Of course it must be recognized that part of the fuel economy penalty can be alleviated by an improved vehicle package. Specific fuel consumption can be made to approach that of a good reciprocating piston engine as evidenced by the performance of several prototype engines. The most significant source of high fuel consumption is leakage past the engine seals. Combustion chamber shape and slow flame travel are minor factors, and the lower friction is a plus.

Cost is a major question because new manufacturing technology is required. Developments in the past year suggest that important gains have already been made. Other areas of difficulty currently being investigated are far less significant and should not influence product acceptance.

One of the most promising areas of future rotary engine development is the application of stratified charge combustion. Curtiss-Wright has published some of the results of their work with a fuel-injected stratified charge engine and report fuel economy data comparable to conventional piston engines. The combustion chamber shape and controlled mixture motion within the engine enhance its potential for use with stratified charge combustion. In addition, there appears to be significant potential for carbureted stratified charge operation of the rotary engine. This, in part, is made possible by the lack of charge mixing during the compression process. It is believed that the second generation of rotary combustion engines might employ the stratified charge principle.

Emissions from the rotary engine are similar to those from a conventional gasoline piston engine since the basic cycle is the same. In general, the hydrocarbon emissions from the uncontrolled Wankel engine are higher than those from the conventional engine, but the NO_x emissions are lower. The carbon monoxide emissions are the same and are primarily a function of the engine fuel-air ratio. There is some evidence to suggest that PNA concentration is higher in the rotary engine. After-engine emission treatment devices, however, appear to reduce the PNA problem significantly. Emission control can be effectively achieved with after-engine treatment as evidenced by Mazda's work with the thermal reactor and efforts at the University of Michigan with thermal reactors, which have exhibited conversion efficiencies in excess of 98%. Catalytic systems are equally effective on the rotary as on the conventional piston engine. Less EGR will be required for NO_x control. Effectiveness of both the catalytic and thermal reactors is enhanced by rapid engine warm-up and high exhaust temperatures. In the future a stratified charge rotary engine may alleviate the need for after-engine exhaust treatment if there is some modification of the post-1975 Federal emission standards.

The rotary engine appears to hold great promise as a potential alternative to the current reciprocating piston engine. Unfortunately, however, definitive data which are required to make an accurate projection are still lacking.

Points Clarified During Question/Answer Period:

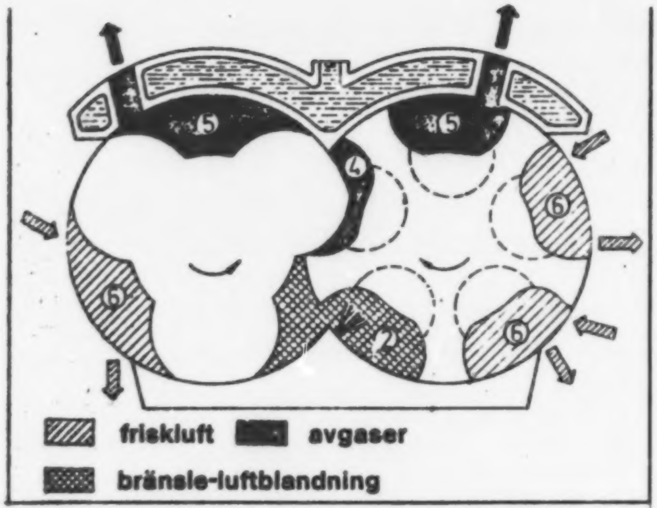
- Some people are looking at single rotor applications where all of the dynamic forces are not balanced; but the comment was made that a flywheel is cheaper than another rotor.
- About 10:1 is the practical maximum compression ratio which can be used in the rotary engine, (above that combustion chamber geometry gets very impractical). Hence the possibility of using the rotary engine principle in a Diesel or compression ignition cycle does not appear to be practical.
- Tests by Army Fuels and Lubricants Lab (with combinations of fuels and lubes) have shown serious effects on seals, seal sticking, and seal performance in air cooled rotary engines. It was suggested that low ash lubricants should be used.
- Heat rejection to coolant and exhaust is about the same as for a conventional engine; however, a critical design area is the high heat flux density in the narrow portion of the engine.

This is a principle reason for the aluminum tracheid housing rather than cast iron housings. Cast iron does not have adequate thermal properties.

- Perhaps the most significant factor in the HC emission is the leakage past the apex seal.
- Spark plug life is not considered a current problem due to surface gap plugs, high energy ignition system, and unleaded fuel.

B. Rotary Engines in Sweden, by Dr. Ljungstrom, Transport Systems R & D Planning, Swedish Board on Technical Development

A twin rotor (male and female) rotary engine was briefly described which is under development by Svenska Rotor-Maskiner (Swedish Rotary Machinery Co.) (See Fig. 148). Each of the two meshing rotors is about 12 inches in diameter and 5 inches long. The engine has been tested to 200 HP, at 2000 rpm and 23% thermal efficiency. It is early in development and is expected to reach 30% thermal efficiency. This type of engine can be designed as a spark ignition or compression ignition engine. It is light weight (about 3.3 lb/HP) and compact. Appropriate power range for this type of engine should be 200 to 1500 HP. It has relatively smooth operation with 3 torque pulses per revolution rather than one as in the Wankel engine. Seals are similar to those in the Wankel engine.


5
5
4
6
6
6
2
▨ friskluft
■ avgaser
▩ bränsle-luftblandning

① R-motorns arbetscykel innehåller dessa moment: 1−2 Kompression med bränsleinsprutning, 3 Förbränning, 4 Expansion, 5 Utblåsning av avgaser, 6 renspolning.

Fig. 148 Schematic of SRM Rotary Engine

VIII. ELECTRIC CAR AND ALTERNATIVE FUELS

A. Impact Study of Electric Cars for Los Angeles, by William Hamilton, Program Manager, General Research Corporation, Santa Barbara, California

This study considers the use of battery-electric cars in the Los Angeles Air Basin for the years 1980, 1990 and 2000 and their possible impact on: environment, resources, economy and society.

Although it focuses on the Los Angeles region, it includes national implications for regional electric car use. Its ultimate concern is the comprehensive impacts of battery-electric car introduction in a conventional-automobile situation; it does not address hybrid-electric, steam, or other automotive alternatives

The study approach begins with parametric analysis which first forecasts likely characteristics of electric cars and then develops their impacts as a function of regional level of use. Impacts are measured relative to a baseline projection built on a conventional automobile system. Prospective levels of electric car usage are estimated separately by constructing upper and lower bounds, and hypothesizing public policy scenarios producing levels in between. Eventually, estimated usages will be combined with parametric results in developing final impact summaries and evaluations.

The characterization of electric cars is being performed under subcontract by Minicars, Inc., of Santa Barbara, California. Figure 149 shows parametric vehicle gross weights for a small shopping car and for a larger car with freeway commuting capability, together with specific range-weight combinations selected for subsequent use in the study. Ranges shown were evaluated on the SAE Residential and Metropolitan Area Driving Cycles, respectively. Maximum ranges at constant speed are over twice the figures shown. Figure 150 shows the performance of the batteries assumed for these 1980 calculations, together with performance of several advanced lead-acid traction batteries which have already been operated in experimental electric cars. Also shown is the performance of a lithium-sulfur battery which

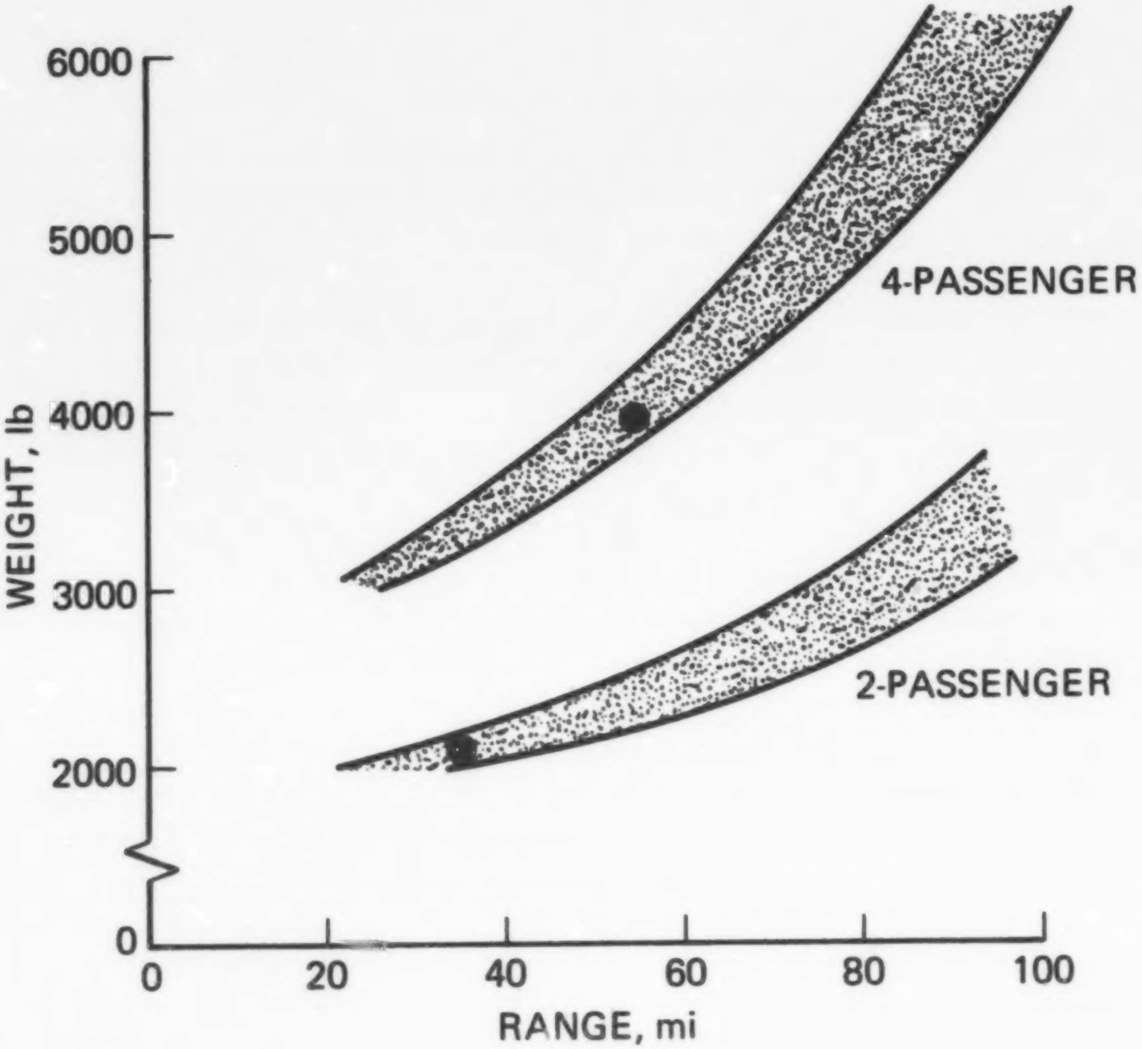


Fig. 149 Electric Car Weight Versus Range — 1980

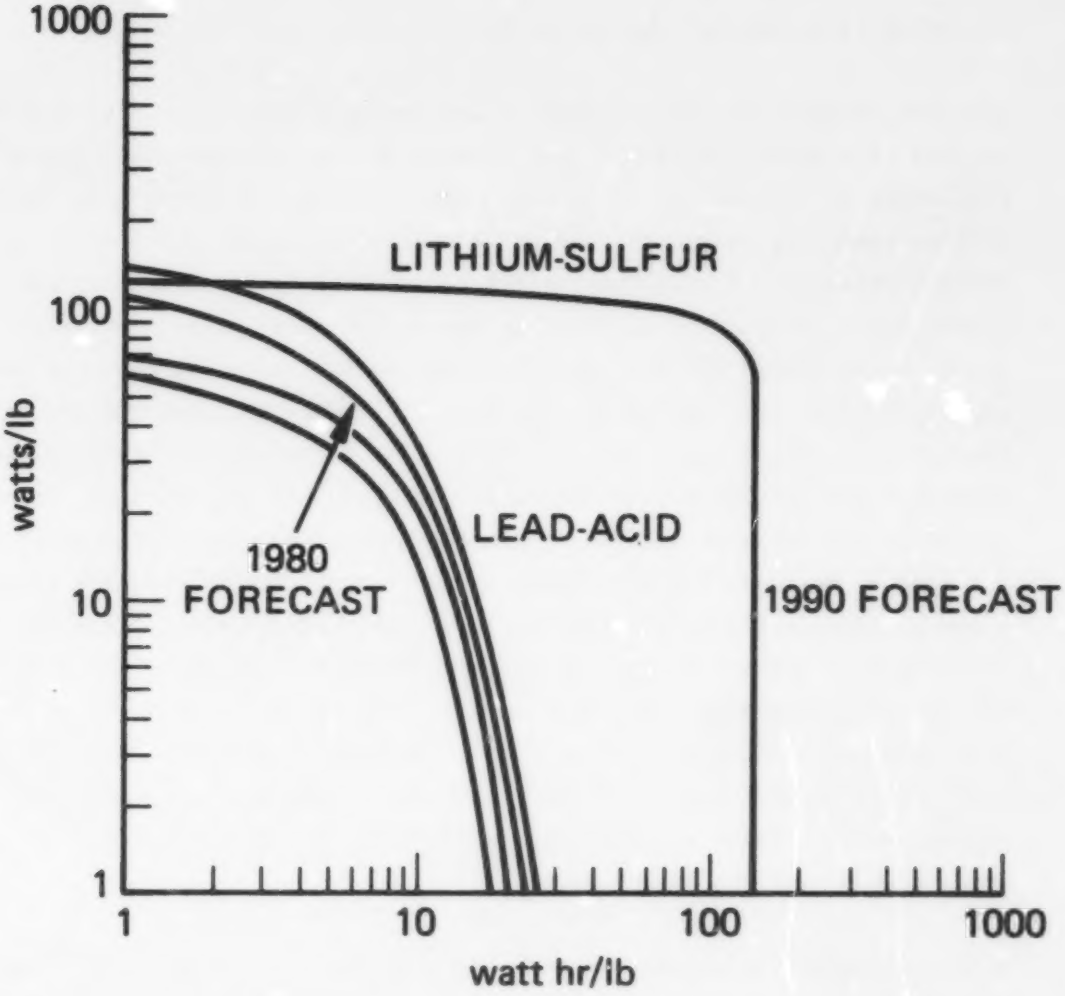


Fig. 150 Battery Characteristics

current development programs are expected to make available by 1990; its superior performance essentially removes electric car range restrictions forecast for 1990. Cost, energy efficiency, and resource requirements are now being projected for the future electric cars.

Baseline projections for Los Angeles are being compiled from a variety of sources as a basis for calculating impacts of electric car use. Regional population is the key factor in this baseline; Fig. 151 shows both the projection currently in general use and a lower projection which reflects the virtual cessation of both immigration and natural increase actually observed since 1970 in the Los Angeles area. The lower projection, with growth rates nearly 50% less than anticipated several years ago, has been adopted for the baseline case. As Fig. 152 indicates, continuation of long-standing trends in growth of automobiles per person is nevertheless projected for the South Coast Air Basin in which Los Angeles lies. The projection is based on detailed regression analysis being conducted by the Los Angeles Regional Transportation Study (LARTS). LARTS' interim forecasts and models (final forecasts have not yet been completed) anticipate not only more automobiles per person, but a dramatic increase in annual mileage per automobile. But as Fig. 153 shows, this increase is not in line with the long-term national trend. In consideration of this discrepancy, plus growing energy and environmental problems, a projection of average vehicle usage much more in accord with the long-term trend is being adopted for the impact study.

With the automobile population and usage projection go a series of economic projections such as that of Fig. 154. In addition to outlining overall economic status, these projections pinpoint those segments of the economy to be impacted as electric car usage increases.

Considerable emphasis in baseline projections has been given to the Los Angeles regional energy situation, since net effects on energy usage and future availability of electric power for battery recharging are crucial in impact analysis. Figure 155 shows projected peak-season hourly demand

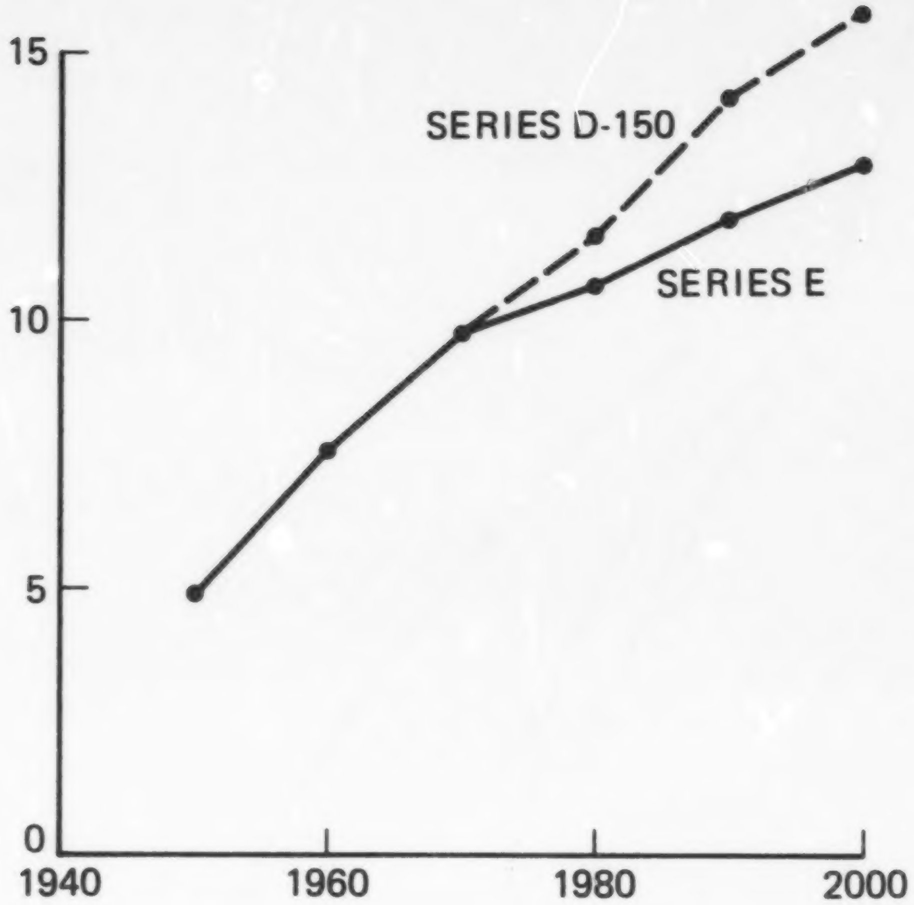


Fig. 151 Population — Millions

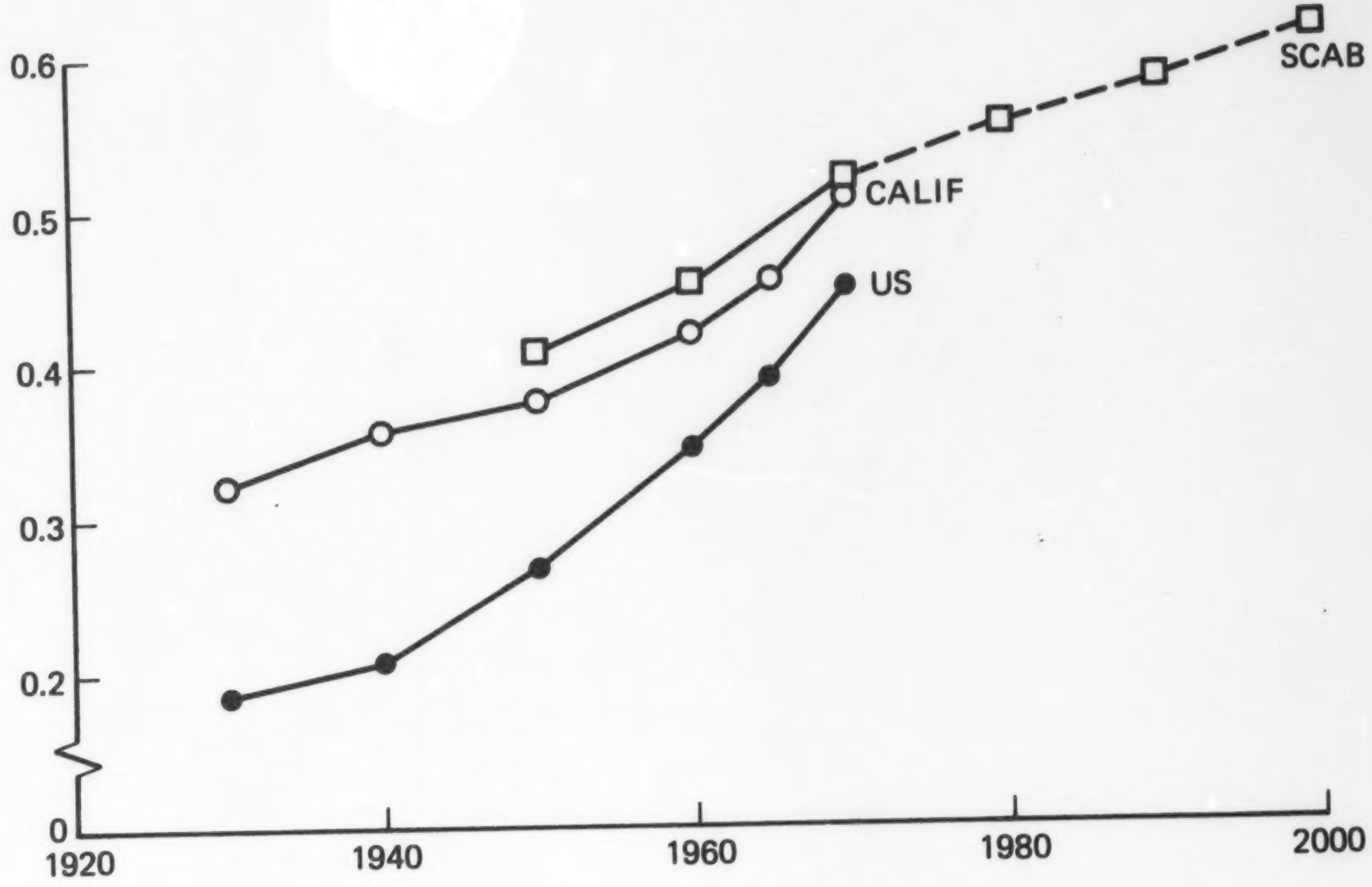


Fig. 152 Automobiles Per Person

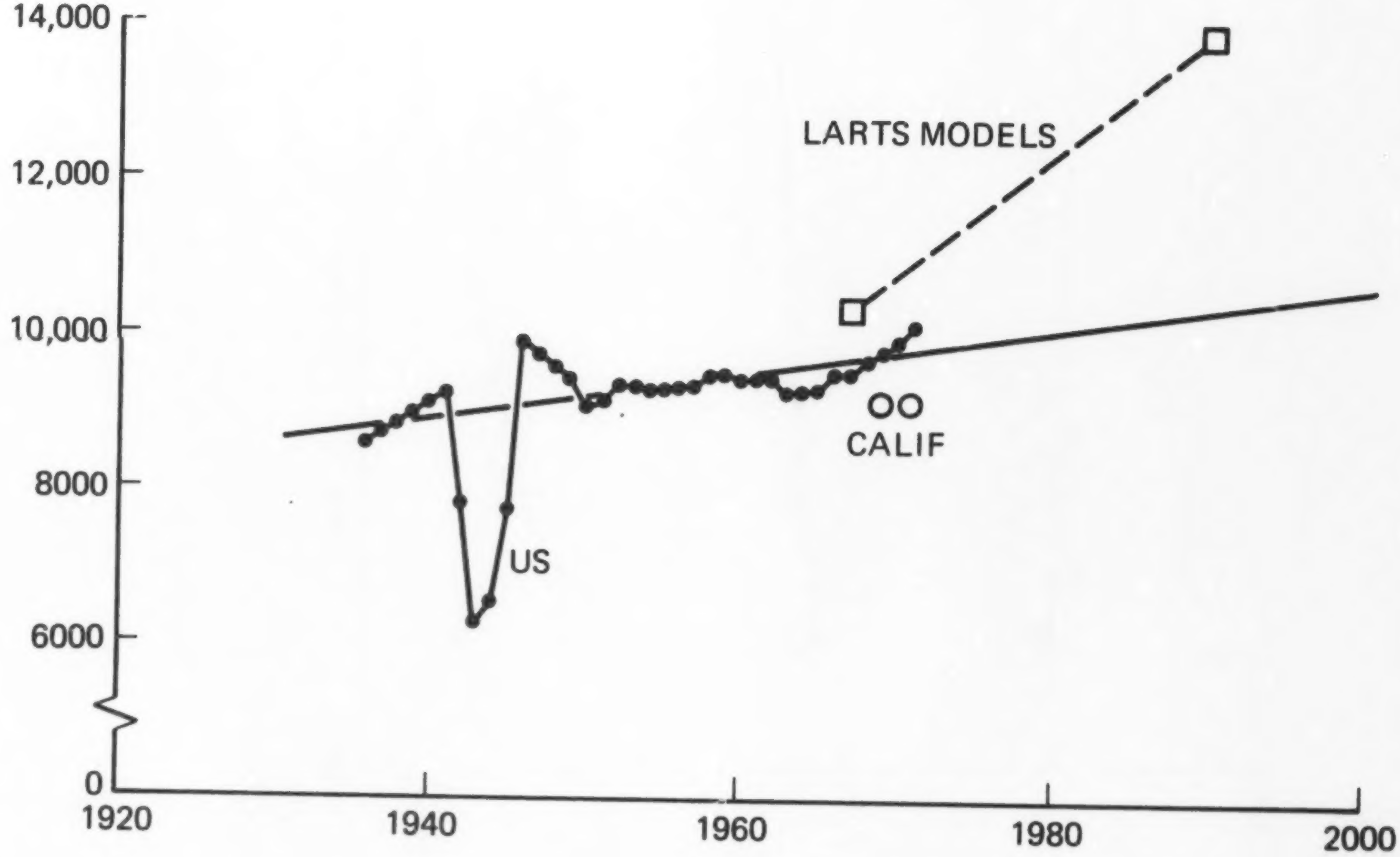


Fig. 153 Average Annual Passenger Car Mileage

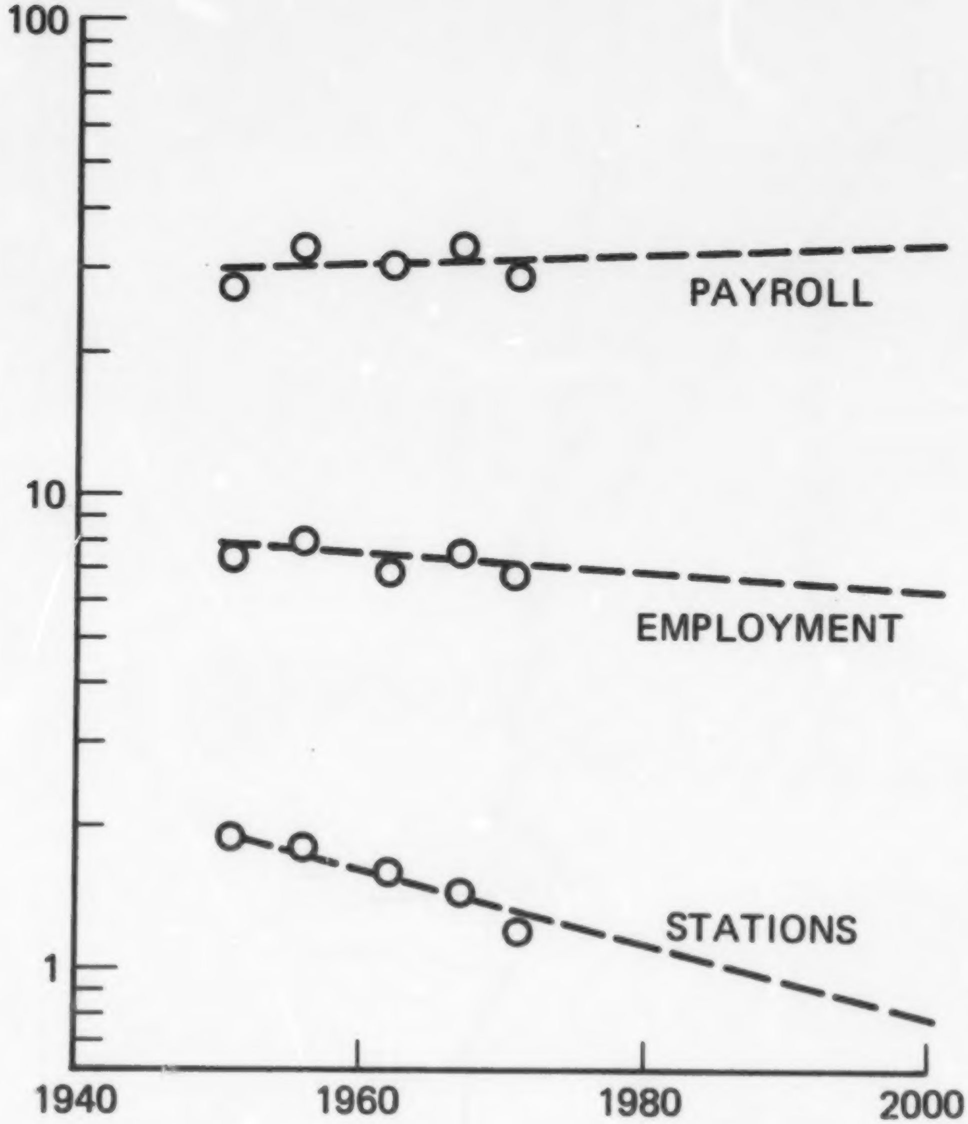


Fig. 154 Service Stations Per 1000 Autos

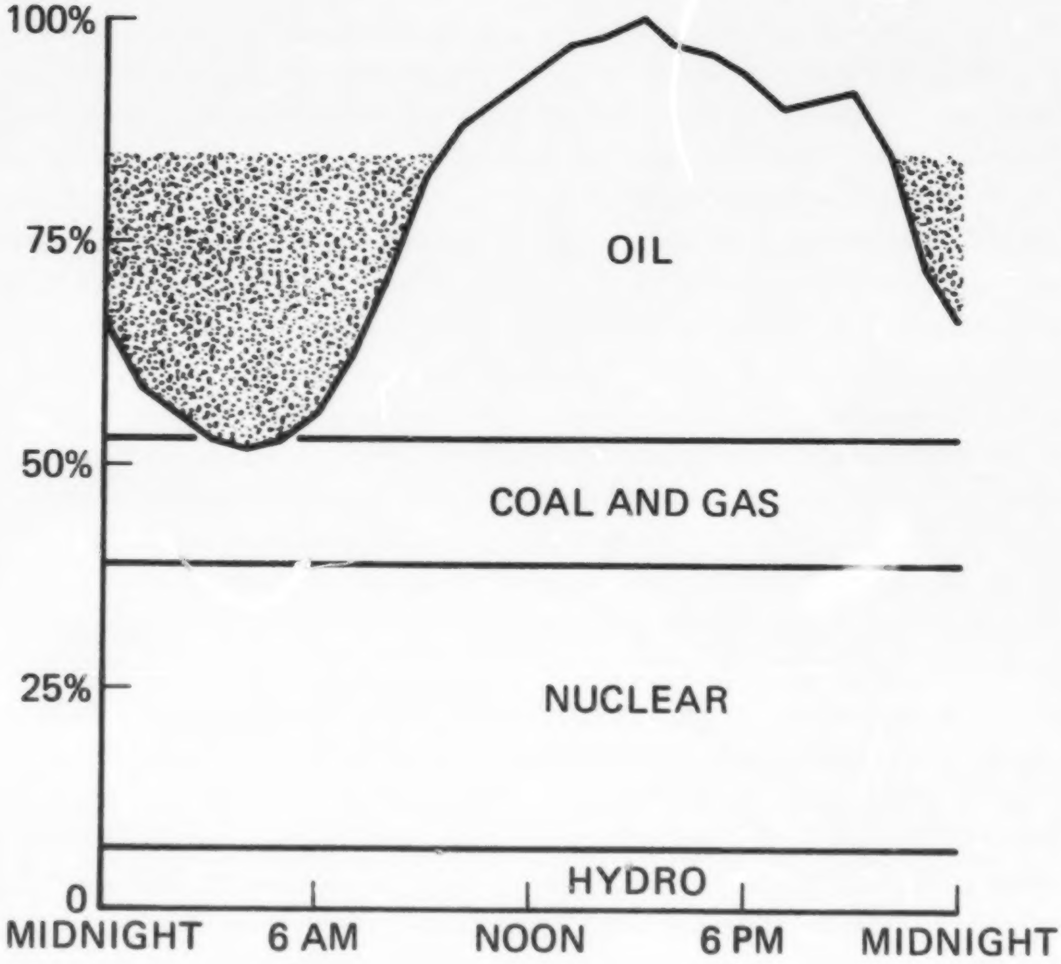


Fig. 155 Hourly Electricity Demand and Supply — Aug 1990

for recharge of electric car batteries. In total, available capacity amounts to almost 90 million kilowatt-hours per day, enough for the majority of daily regional vehicle-miles to be supplied by electric cars.

As Fig. 156 shows, oil-fired electric plants, which are generally located in the South Coast Air Basin, are likely to be used for peaking in 1990 since their higher fuel costs and air pollutant emissions are to be avoided where possible. Thus electric car recharging will likely be accompanied by substantial additional power plant emissions. The consequence of this is difficult to calculate because added emissions appear at night rather than in the daytime, at isolated coastal points rather than throughout the Basin and comprise a different pollutant mix. Accordingly, air quality impacts of electric car use will be addressed through a series of runs of a detailed photochemical diffusion model. The model accounts for emissions at different times and places, together with realistic meteorology and chemistry. Through its use, air quality relative to prospective standards will be determined for key sites in the Los Angeles Air Basin.

Once these and other parametric impact forecasts are completed, they will be combined with results of the electric car usage analysis. These results will show the extent to which limited-capability electric cars are capable of the trips which people actually took in a recent year. Together with a market share analysis based on auto size and other performance indicators, this will enable development of a lower bound on electric car use corresponding to penetration in a market essentially as we know it. An upper bound will also be projected based on probable future rates at which electric cars could be manufactured and brought into the auto population. Figure 156 suggests likely intermediate levels of use will then be developed for hypothetical public policy scenarios which will variously promote electric cars and penalize the conventional-car competition. Such scenarios are now actually beginning as the nation faces its prospective energy needs and air quality requirements.

The study will conclude with construction and evaluation of impact ledgers,

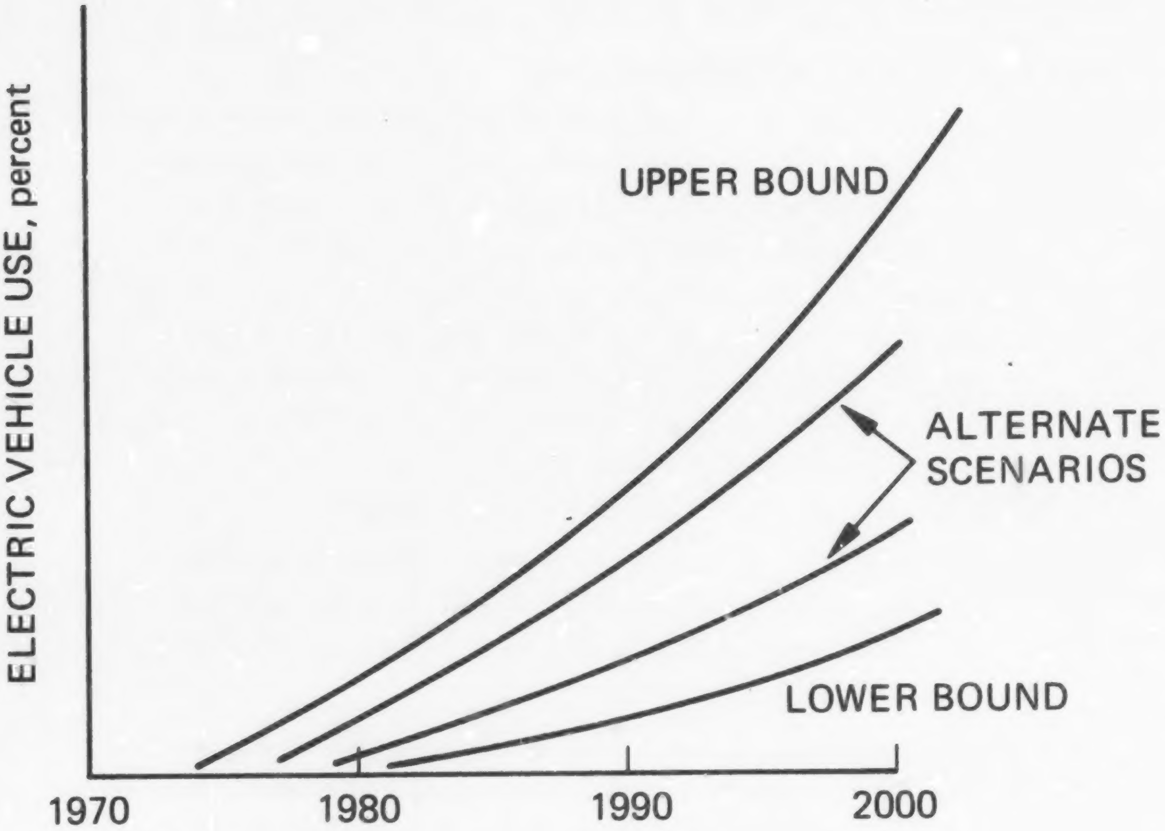


Fig. 156 Usage Forecasts

as outlined in Fig. 157 summarizing overall quantitative results and serving as a basis for evaluation and conclusion of desirable levels of electric-car use in the Los Angeles region. The final project report is to be completed in June, 1974.

Points Clarified During Question/Answer Period:

- There is some concern about safety problems pertaining to the relatively small low performance electric vehicles in a mixture of traffic with larger, higher performance cars driven by I.C. engines. There is a healthy weight allowance in the vehicle for safety provisions. Although the car can keep up with traffic at freeway speeds (60 mph), its acceleration is 4 mph per second at 25 mph. Also from a crash-worthiness viewpoint, the car is rather heavy for a small vehicle. Due to the batteries, there is difficulty in getting sufficient "crush stroke" within the constrained geometry.
- For the study, the hypothetical vehicles were characterized parametrically, and range-weight characteristics were based on SAE J227 "Recommended Procedure for Reporting Electric Vehicle Performance".
- Assumptions will be made about electric car ownership based on existing patterns of automobile ownership and expected performance capabilities of electric cars. Many households in the Los Angeles area already own two or more automobiles.

B. Alternative Fuels, by Dr. Jon Pangborn, Program Manager, Institute of Gas Technology, Chicago, Illinois

EPA recently initiated two contracts (one with IGT and the other with Esso Research and Engineering- see Section IX-C) which are being conducted to the same work statement because of the broad nature of the problems and the uncertainties inherent in the area of technological and economic forecasting.

	USE, %	AIR QUALITY	ENERGY USAGE	EMPLOYMENT	TRAVEL MPH, $
1970 ACTUAL					
1980 BASE					
SCENARIO A					
SCENARIO B					
1990					
2000					

Fig. 157 Electric Car Impact Ledger

The objective of these contracts is to identify the most promising domestic, non-petroleum derived fuels which would permit a reduction in the automotive use of petroleum while providing acceptable performance, emissions, and economy. Benefits and penalties along with the problem areas associated with these alternative fuels are to be identified.

The Institute of Gas Technology is pursuing the above objective in a four-phase program as follows:

Phase One - Assembly of Background Information

- Energy and material resource analysis
- Energy and material conversion, synthesis technology
- Fuel properties and combustion characteristics
- Fuel-engine-vehicle requirements and compatibility

Phase Two - Selection of Technical and Economic Criteria and Procedures

- Resource conversion, storage, distribution cost
- Vehicle costs - fuel system, engine, body
- Competing demands for fuels
- Environmental constraints
- Technological readiness
- Recommendation criteria and fuels selection

Phase Three - Detailed Assessment of Fuel Candidates

- Energy source, fuel synthesis, storage, distribution
- Vehicle characteristics, efficiency, economics
- Effects of competition for fuels
- Environmental effects - resource extraction, fuel synthesis and utilization
- Technological readiness, identification of gaps
- Final selections and characterizations

Phase Four - Development of Recommendations and Scenarios

- Recommended alternative fuel(s), scenarios (characterization of recommended alternative fuels system - technical, economic, social effects; scenarios for time periods)

Figure 158 shows initial considerations for energy sources and auxiliary materials. Figure 159 shows potential automotive fuels and the engine cycles.

Points Clarified During Question/Answer Period:

- Some consideration is being given to the possibility of generating hydrogen on the vehicles as it is needed. This would avoid the storage and handling problems of hydrogen. Although some laboratory tests have shown feasibility, the technology and economic practicability are highly questionable at this point. Also, so far, the hydrogen source is gasoline, hence it really doesn't answer the problem posed for this program.

C. Alternative Fuels, by Dr. Fred Kant, Program Manager, Esso Research and Engineering Company, New Jersey

The overall work plan (Fig. 160) summarizes the steps to be taken in fulfilling the requirements of the EPA concract. An initial list of fuels willbe screened to select a few for in-depth analysis. This analysis will feature detailed economics of manufacture and distribution, compatibility with existing systems, and assessment of technological status. The resultant recommendations will indicate the fuel of choice for each time frame, as well as a suggested entry strategy and definition of research and development needs. Throughout the contract, relevant background studies will be carried out in areas such as total fuel demand and resource base evaluations.

An initial list of candidate fuels has been prepared (Fig. 161). It includes conventional fuels from unconventional sources, such as shale and coal liquids, as well as unconventional fuels, such as alcohols, hydrogen,—

ENERGY SOURCES

- COAL
- SHALE OIL
- TAR SANDS
- URANIUM AND THORIUM
- NUCLEAR FUSION
- SOLAR RADIATION
- SOLID WASTES (GARBAGE)
- ANIMAL WASTES
- WIND POWER
- TIDAL POWER
- HYDROPOWER
- GEOTHERMAL HEAT

AUXILIARY MATERIAL SOURCES

- AIR (O_2, CO_2, N_2)
- ROCK (LIMESTONE)
- WATER
- LAND

Fig. 158 Initial-Consideration List

ACETYLENE
AMMONIA
CARBON MONOXIDE
COAL
DIESEL OILS
ETHANOL
FUEL OILS
GASOLINES (C_5- C_{10})
HEAVY OILS

HYDRAZINE
HYDROGEN
KEROSENES
METHANOL
METHYL AMINES
SNG (C_1- C_2)
NAPHTHAS
VEGETABLE OILS

CYCLES

BRAYTON
DIESEL
OTTO

RANKINE
STIRLING
FUEL CELL AND MOTOR

Fig. 159 Potential Automotive Fuels

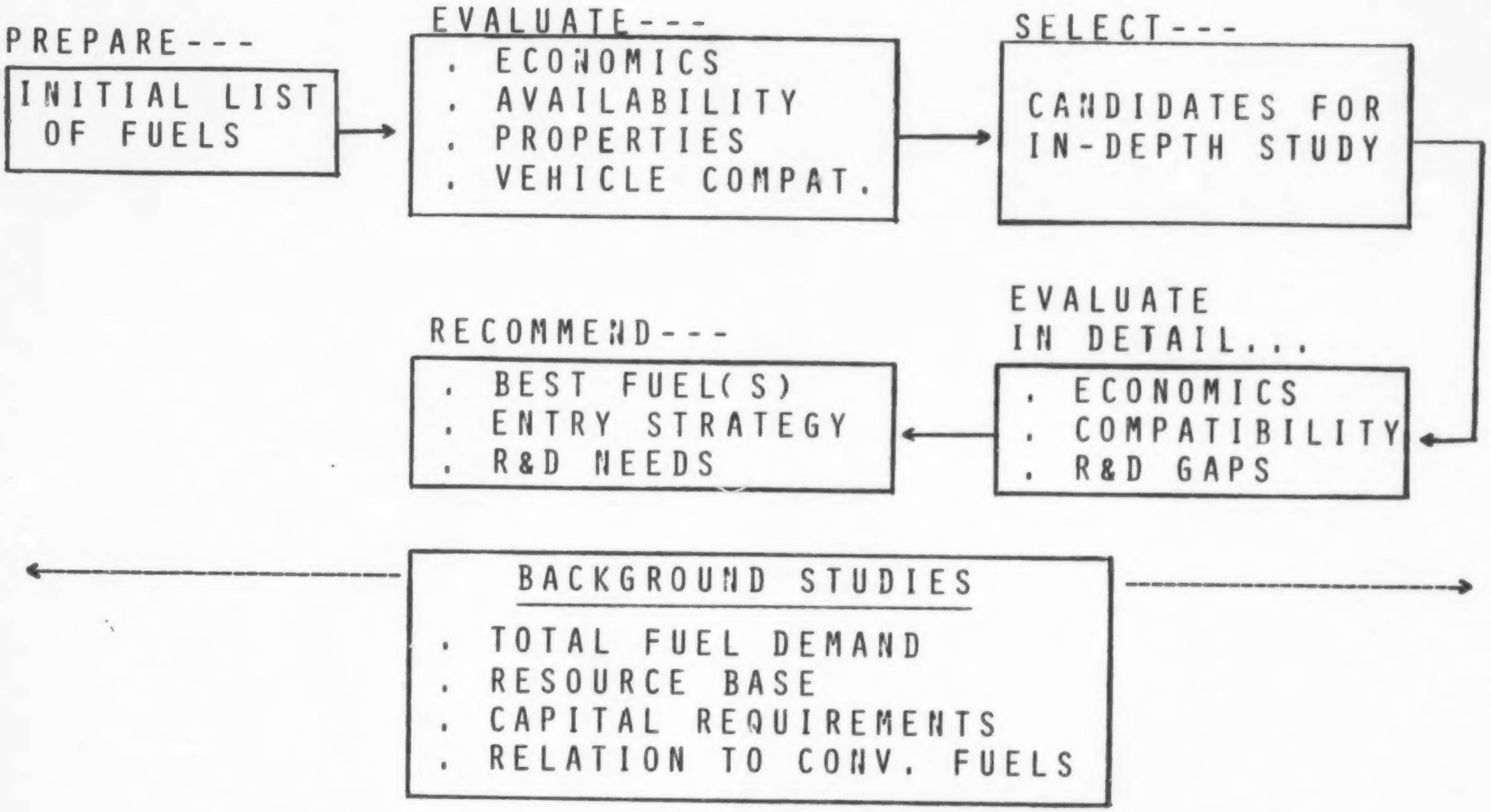

PREPARE---
INITIAL LIST OF FUELS
EVALUATE---
. ECONOMICS
. AVAILABILITY
. PROPERTIES
. VEHICLE COMPAT.
SELECT---
CANDIDATES FOR IN-DEPTH STUDY
EVALUATE IN DETAIL...
. ECONOMICS
. COMPATIBILITY
. R&D GAPS
RECOMMEND---
. BEST FUEL(S)
. ENTRY STRATEGY
. R&D NEEDS
BACKGROUND STUDIES
. TOTAL FUEL DEMAND
. RESOURCE BASE
. CAPITAL REQUIREMENTS
. RELATION TO CONV. FUELS

Fig. 160 Overall Program Plan

FUEL	SOURCE	PROCESS
GASOLINE	COAL	HYDROG., PYROLYSIS, F/T
DISTILLATE	SHALE	RETORTING + REFINING
METHANOL	COAL	FROM CO/H_2
ETHANOL	CARBOHYDR.	FERMENTATION
HIGHER OXYGENATES	COAL	FISCHER / TROPSCH
HYDROGEN	COAL	GASIFICATION
	WATER	ELECTROLYSIS, THERMAL
METHANE	COAL	GASIFICATION
AMMONIA	COAL (H_2)	GASIFICATION + SYNTHESIS
	WATER (H_2)	ELECTROLYSIS + SYNTHESIS
HYDRAZINE	AMMONIA	SYNTHESIS

Fig. 161 Initial Fuel Candidates

and ammonia. In keeping with the work statement, only fuel sources other than petroleum were considered. A variety of processes will be considered for manufacturing the fuels selected. The list was restricted to those fuels which could conceivably be produced in large enough volumes to satisfy a substantial portion of future automotive fuel demand.

The selection of the most promising candidates from the initial list will be made on the basis of various criteria (Fig. 162). As indicated, not all of the criteria tabulated will be considered in the initial screening. The most important criteria are: (1) cost of manufacture and distribution, (2) availability, (3) vehicle compatibility, (4) toxicity and safety, and (5) efficiency of use.

An initial estimate was made of the cost of manufacturing and distributing the various fuels (Fig. 163). The costs are compared on the basis of constant energy content and for a fixed scale corresponding to the gasoline production of a large U.S. petroleum refinery. Distribution costs represent a substantial fraction of the ex tax cost of the fuel to the consumer. These costs were estimated from assumed, simplified distribution networks. For example, coal and shale "syncrude" was prepared near the mine and pipelined to a Chicago refinery, from which gasoline and/or distillate was distributed in an analogous fashion to conventional petroleum products. Methanol from coal produced at the mine was pipelined to various bulk terminals for local distribution. Hydrogen by water electrolysis was liquefied nearby and distributed as a liquid to a bulk terminal and to the consumer. Methane from coal was pipelined from a mine-mouth gasification plant to liquefaction plants and distributed in a fashion similar to hydrogen.

Another of the selection criteria involves the fuel availability (Fig. 164) which defines the earliest date at which the fuel can be made available, either due to the need to develop the technology, or just due to normal delays in designing, financing, and constructing large capital projects. On the whole, none of the fuels can be made available in substantial quantities before the mid-1980's. In cases such as fuels derived from coal, existing technology, which has definite shortcomings, could be used to

ECONOMIC:	+	COST OF MANUFACTURE AND DISTRIBUTION
	+	OPERATING COST IN VEHICLE
TECHNICAL:	+	TECHNOLOGICAL STATUS: FUEL AVAILABILITY
	-	EFFICIENCY OF FUEL PRODUCTION
	-	ENVIRONMENTAL IMPACT IN PRODUCTION
PERFORMANCE:	+	COMPATIBILITY WITH VEHICLE AND ENGINE
	+	TOXICITY
	+	SAFETY
	+	DRIVER ACCEPTABILITY: CONVENIENCE
	+	EFFICIENCY OF USE
	+	ENVIRONMENTAL IMPACT IN USE
STRATEGIC:	+	FUEL SHIFT COMPATIBILITY; ENTRY STRATEGY
	-	RESOURCE AVAILABILITY
	-	INTERNATIONAL CONSIDERATIONS

(+) INDICATES CRITERIA CONSIDERED IN INITIAL SCREENING

Fig. 162 Criteria for Fuel Selection

	$/MMBTU*		
	MANUFACTURE	DISTRIBUTION	TOTAL
SHALE GASOLINE	1.25	1.00	2.25
SHALE DISTILLATE	1.10	1.00	2.10
COAL GASOLINE	1.90	1.00	2.90
COAL DISTILLATE	1.65	1.00	2.65
METHANOL (COAL)	1.55	1.00	2.55
ETHANOL (CARBOHYDR.)	5.00	0.90	5.90
HYDROGEN (NUCLEAR)	4.60	4.00	8.60
METHANE (COAL)	1.50	2.30	3.80
AMMONIA (NUCLEAR)	6.25	1.40	7.65
HYDRAZINE	21.	---	
GASOLINE	1.50	1.00	2.50

BASIS:

1973$, MANUF. SCALE 6×20^{11} BTU/DAY (6.3×10^{11} KJ/DAY) CORRESPONDING TO 100,000 B/D (4.2 MILL. TON/YR.) GASO.

Fig. 163 Preliminary Fuel Economics

FUEL	EARLIEST AVAILABLE DATE
SHALE LIQUIDS	1980
COAL LIQUIDS	1980 (F/T OR PYROL.)
	1983 (HYDROG.)
METHANOL	1978 (LURGI GASIF.)
	1980 (IMPR. GASIF.)
ETHANOL	1978
HYDROGEN	1978 (COAL - LURGI)
	1980 (COAL - IMPR. GASIF.)
	1985 (ELECT. - BASE LOAD)
METHANE	1978 (COAL - LURGI)
	1980 (IMPR. GASIF.)
AMMONIA	SAME AS H_2

Fig. 164 Availability of Potential Automotive Fuels

introduce the fuel a few years sooner while improved technology is being commercialized.

The availability of any fuel is an obviously necessary but hardly sufficient criterion for its use. Another important area is fuel compatibility with the vehicle (Fig. 165). Initially, this issue is being addressed by considering qualitatively the modifications that have to be made to vehicles with various power plants in order to burn each of the fuels being considered. The use of gasoline or distillate from shale would require essentially no modifications compared to operation with the petroleum-derived analogues. Similar products derived from coal would require some engine modifications due to the high aromaticity of the fuel. Vehicles powered by methanol would require some modifications reflecting its lower energy content and higher heat of vaporization relative to ordinary gasoline. Both methanol and gasoline from coal, however, could readily be used in blends with petroleum-derived fuels. The use of hydrogen or ammonia would require substantial modifications to the power plant as well as the fuel storage and handling system.

The physical and chemical properties of the candidate fuels are another set of criteria to be considered in selecting those for in-depth study (Fig. 166). For purposes of convenience, the properties were grouped according to various aspects of vehicle operation: combustion behavior, fuel storage and handling, and automotive maintenance. A detailed literature search yielded a fair amount of property data, but a significant number of properties for various fuels were not available and, wherever possible, had to be estimated.

The choice of fuels for in-depth study is now imminent based on the above criteria. Detailed analysis of the most promising candidates will begin in late October. The analysis is to be completed by March 1974. Final recommendations on fuels, entry strategy, and research and development needs, will be made by May 1974.

ENGINE / FUEL	RECIPROCATING & ROTARY OTTO	RECIPROCATING & ROTARY STRAT. CHARGE	DIESEL	BRAYTON RANKINE STIRLING
PET. GASOLINE	4	4	2	4
PET. DISTILL.	1	2	4	4
SHALE GASOLINE	4	4	2	4
SHALE DISTILL.	1	2	4	4
COAL GASOLINE	3	3	2	3
COAL DISTILL.	1	2	3	3
ALCOHOLS	3	3	2	3 - 4
HYDROGEN	2	2	1	2
AMMONIA	2	2	1	2

SCALE: 1 - NOT PRACTICAL
2 - MAJOR MODIFICATIONS REQUIRED
3 - MINOR MODIFICATIONS REQUIRED
4 - NO MODIFICATIONS REQUIRED

Fig. 165 Compatibility of Fuels and Vehicles

RELATED TO:

COMBUSTION BEHAVIOR	FUEL STORAGE AND HANDLING	AUTOMOTIVE MAINTENANCE
VOLATILITY	DENSITY	OCTANE NO.
HEAT OF COMB.	VISCOSITY	SULFUR
STOICHIOM. MIX	FREEZING POINT	ASH
OCTANE NO.	FLASH POINT	CARBON RESIDUE
MAX. FLAME SPEED	SOL. IN/FOR H_2O	CORROSIVITY
FLAMM. LIMITS	STORAGE STAB.	EMULSION TEND.
EXHAUST EMISSIONS	TOXICITY	SLUDGE TENDENCY
	SAFETY	
	CORROSIVITY	
	VOLATILITY	

Fig. 166 Properties of Candidate Fuels

Points Clarified During Question/Answer Period:

- Some two-thirds of the distribution cost represents the service station marketing including the depreciation cost of the equipment in the service station. Very detailed calculation procedures are used to determine incremental cost of the alternate fuels over current gasoline levels.
- Methanol has almost the same octane level of current gasoline.
- Growth trends in aviation industry are currently quite large (12% - 14% per year). Although it is hard to believe that this rate will continue, it does constitute another demand possibly of higher priority, for petroleum fuels. Aviation is perhaps a more likely user of hydrogen fuel (since it is more weight limited) than automotive which is also volume limited. Hydrogen has a lower heating value of about 52,000 BTU per lb, whereas gasoline has 20,000 BTU per lb. It was mentioned that some hydrogen fueled aircraft were now in early design stages.
- Of several alternate fuels, the main sources are shale and coal. Production of fuels from these sources will raise some environmental problems. Shale has problems with disposing of spent shale and the water from the mining process. Coal has a strip mining problem. These are problems associated with the traditional mining process. However, if in situ (in place) gasification or processing of deep deposits is developed, this would have very little environmental impact.

IX. HYDROGEN FUEL USAGE

A. Partial Hydrogen Injection Into Internal Combustion Engines, by Robert Breshears, Project Engineer, NASA, Jet Propulsion Laboratory, Pasadena, California

A high-efficiency, low-emission engine development project is currently underway at JPL, sponsored by NASA. The concept and current status for the first 5 months of a 7-month feasibility demonstration project are described.

The system under development has the potential of meeting the EPA 1977 Standards, with improved fuel economy as compared with uncontrolled engines. It uses current fuels; engines will have response characteristics similar to current engines and will be low in cost considering both initial cost and fuel savings.

The concept is to use small amounts of hydrogen to allow burning of gasoline at ultra-lean conditions. The hydrogen is generated aboard the vehicle by feeding gasoline, water, and air to a hydrogen generator which produces hydrogen and carbon monoxide. The generated gas is mixed with gasoline and fed to a conventional engine. The required hydrogen is produced in the generator and no hydrogen is stored aboard the vehicle. (See Fig. 167)

In the initial single cylinder CFR engine work, emissions from various fuels were compared in terms of grams of emission per horsepower hour produced and combustion conditions expressed in terms of equivalence ratio. In CFR engine experiments it was shown that NO_x emissions from gasoline could be reduced slightly by lean operation. Levels equivalent to the EPA 1977 standard could not be achieved because misfire limits the minimum equivalence ratio to about 0.63. With hydrogen, however, the engine was operated down to equivalence ratios of 0.1 where the NO_x emissions are less than 1/100 of the EPA Standard and, in fact, down to the EPA ambient air standard (0.25 ppm) (See Fig. 168). Since the extremely low NO_x emissions achievable by lean combustion with pure hydrogen are not required, it is more practical to use small amounts of hydrogen to extend the operating

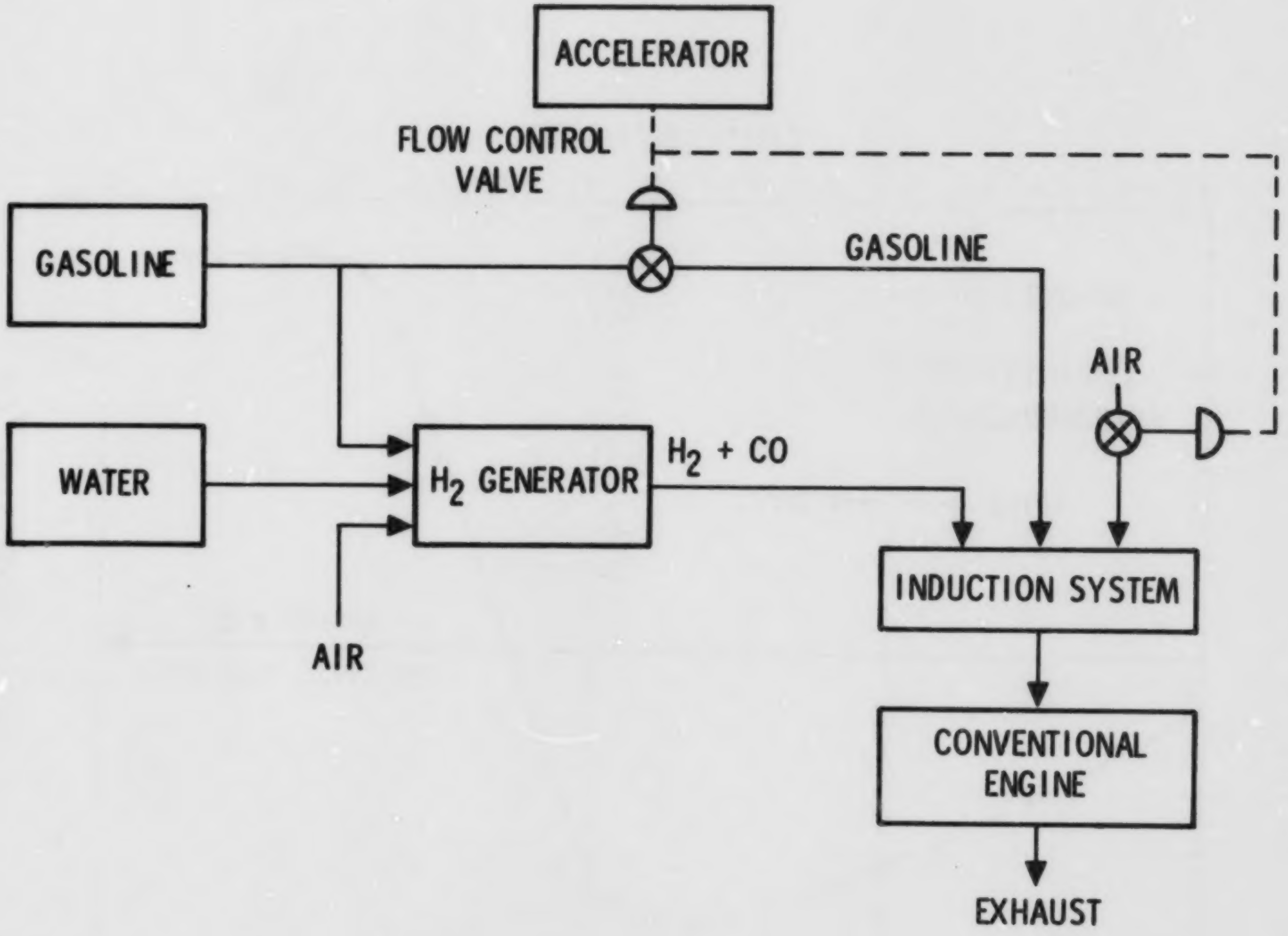

ACCELERATOR
FLOW CONTROL VALVE
GASOLINE
GASOLINE
AIR
WATER
H_2 GENERATOR
H_2 + CO
AIR
INDUCTION SYSTEM
CONVENTIONAL ENGINE
EXHAUST

Fig. 167 JPL System

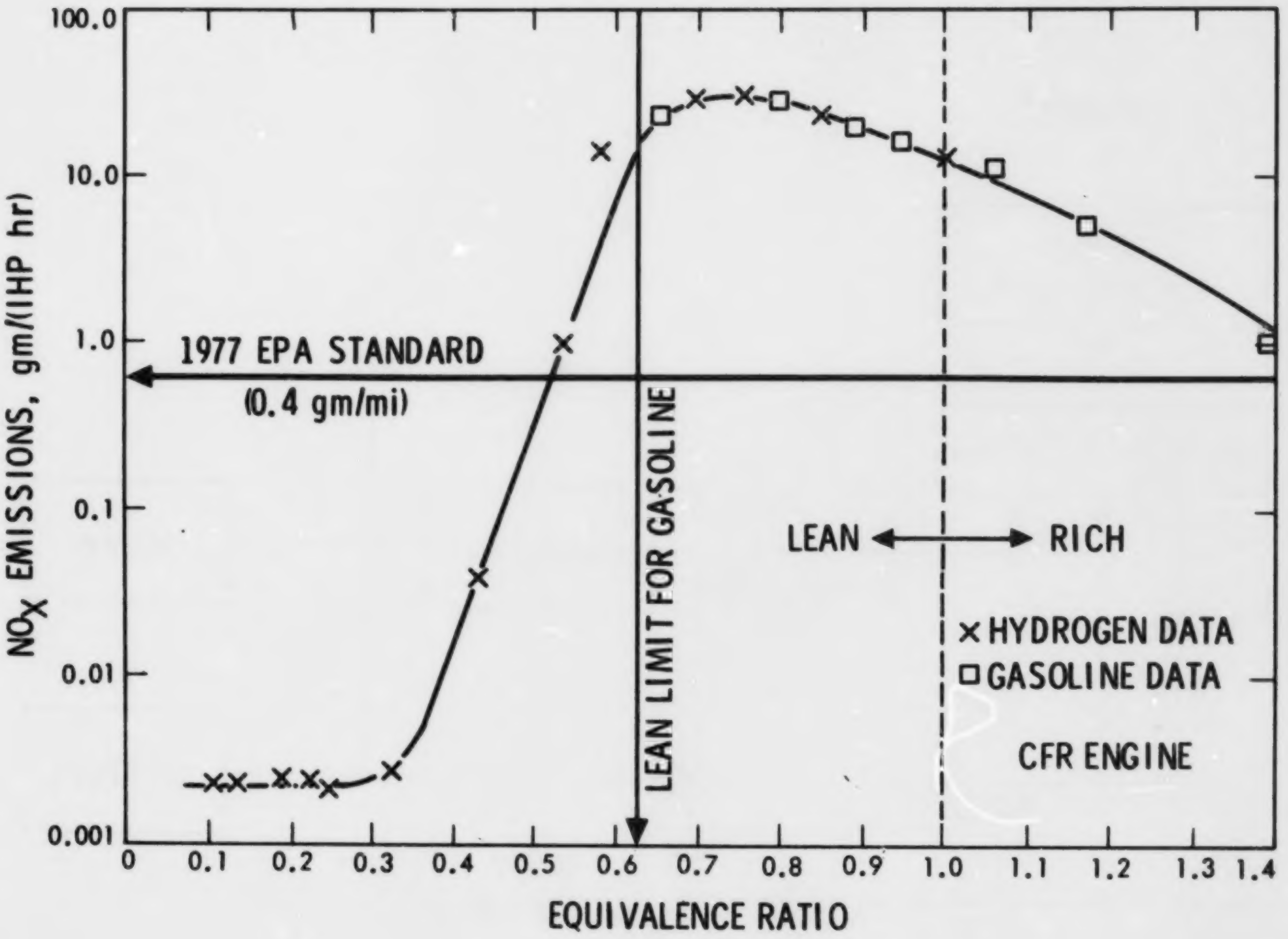


Fig. 168 NO_x Emissions

range for gasoline down into the ultra-lean region. It is desirable to limit the amount of hydrogen needed to minimize the generator size and reduce the effect of generator inefficiency on overall fuel economy. Mixtures of hydrogen and gasoline in both the CFR and V-8 engines showed very low NO_x emissions in the ultra-lean region (Fig. 169). Carbon monoxide emissions were measured and found also to be below the EPA 1977 Standards, as long as adequate quantities of hydrogen were used to avoid misfire. Hydrocarbon emissions have been measured and found to be above the EPA 1977 Standard.

Further work will be needed to reduce hydrocarbon emissions. The engine thermal efficiency was measured and found to be substantially increased (25 to 50%) by operation in the ultra-lean region (Fig. 170). The current hydrogen requirements to avoid misfire are about 5% hydrogen by weight in fuel at an equivalence ratio of 0.6. The theoretical lean limit is 1% by weight of hydrogen, and thus a dramatic reduction in hydrogen requirements appear possible by improvements in the induction system, ignition system, and engine (Fig. 171).

The most critical development of this system is the hydrogen generator. The design chosen is similar to that used for commercial production of hydrogen from hydrocarbons. (The process is called steam reforming.) In this process, gasoline and water are heated to 1500 - 2000°F forming hydrogen, carbon monoxide, plus various hydrocarbons and diluents. Heat is supplied by pumping air into the generator and burning a portion of the gasoline. The reaction takes place in a thermal reactor without the use of catalysts. This design allows rapid startup since the thermal inertia can be made small; it allows the use of low-cost materials since the container need not operate at reaction temperatures; and it avoids potential catalyst poisoning problems.

The maximum theoretical hydrogen yield for this type of generator is 29% as compared with current generators which yield 15-20% hydrogen output. An operating condition has been found where soot is not produced. Further development will be directed toward completely eliminating the need for water. When the current generator is operated without water, larger

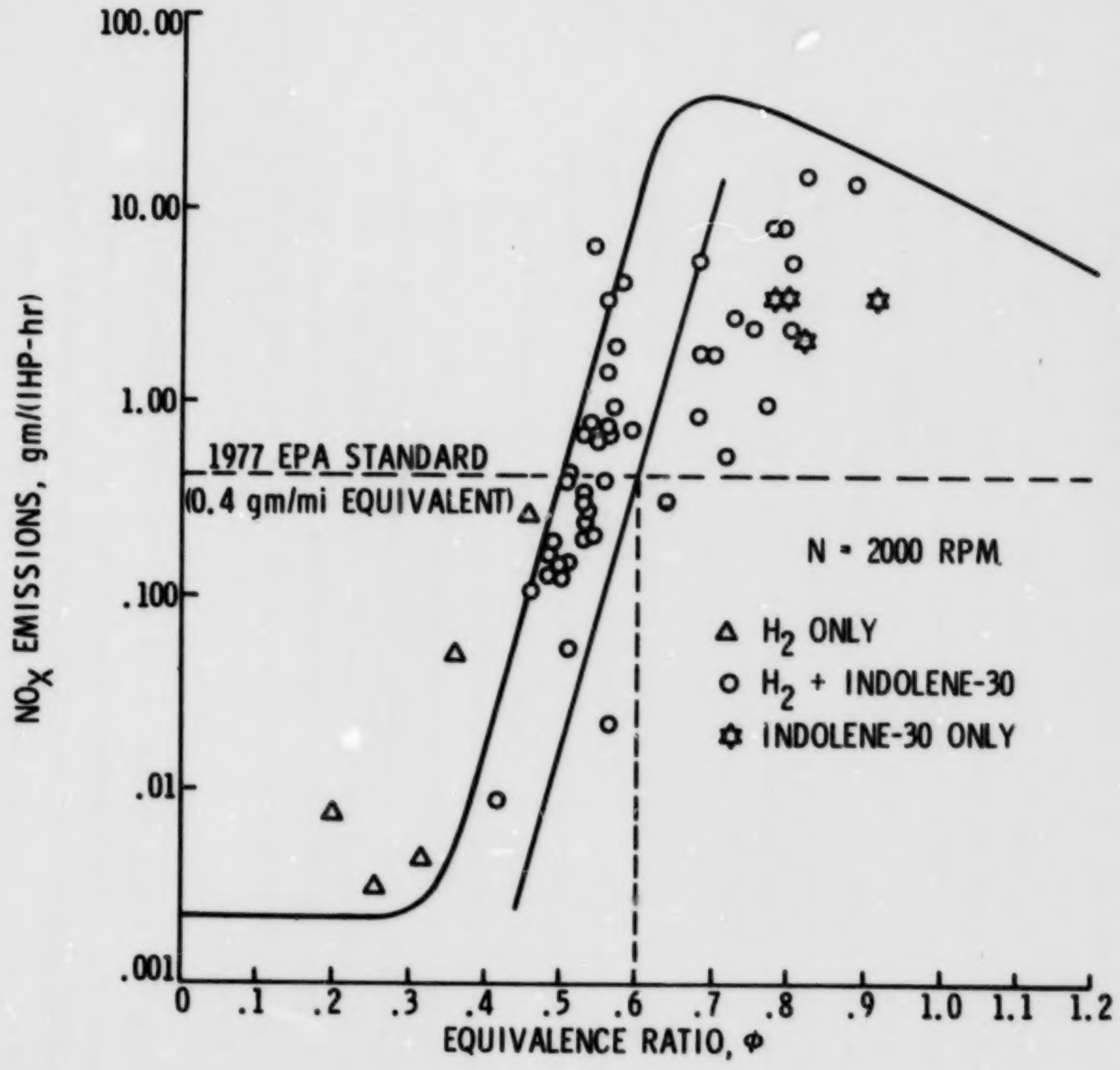


Fig. 169 NO$_x$ Emissions — V-8 Engine

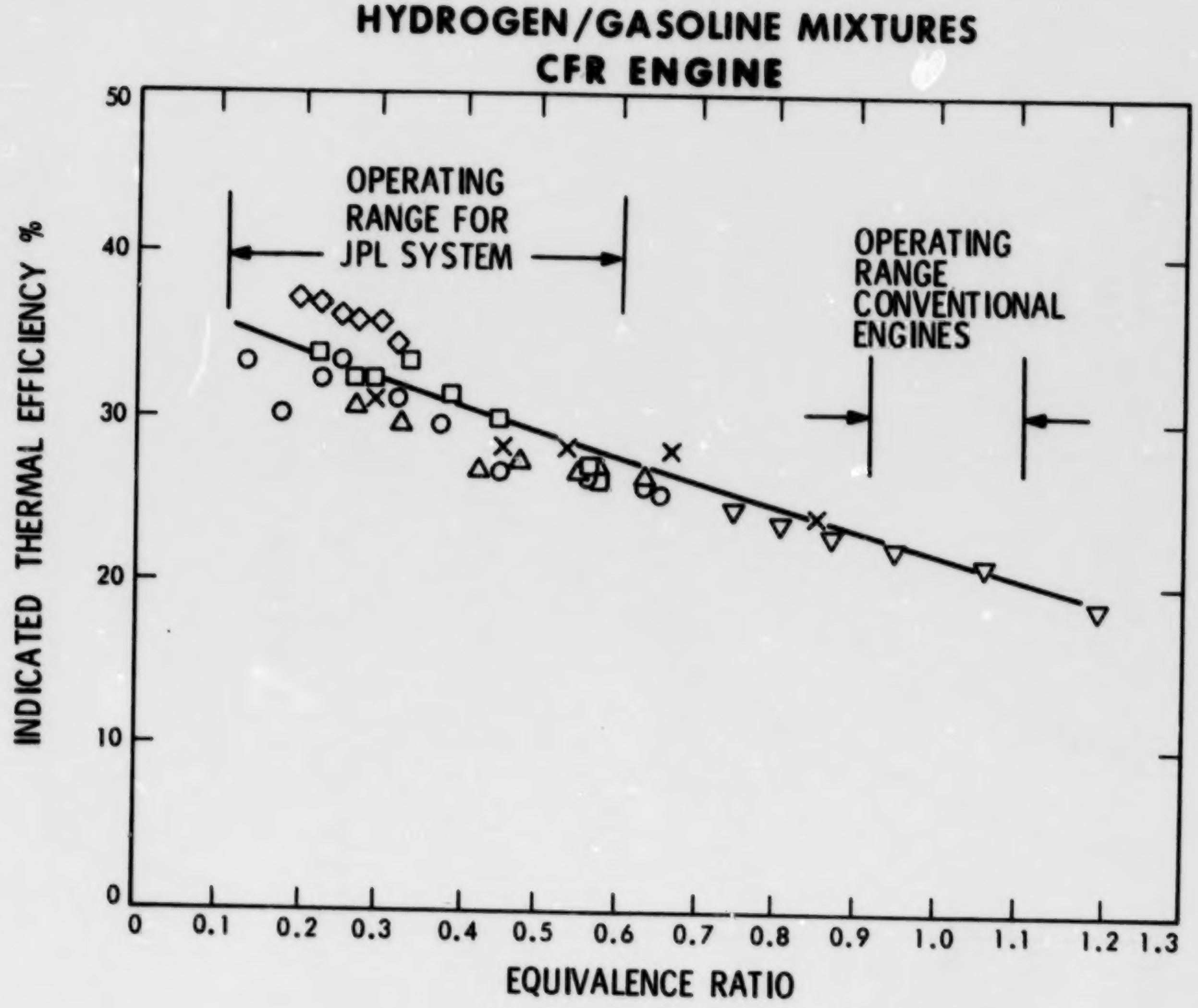


Fig. 170 Engine Thermal Efficiency

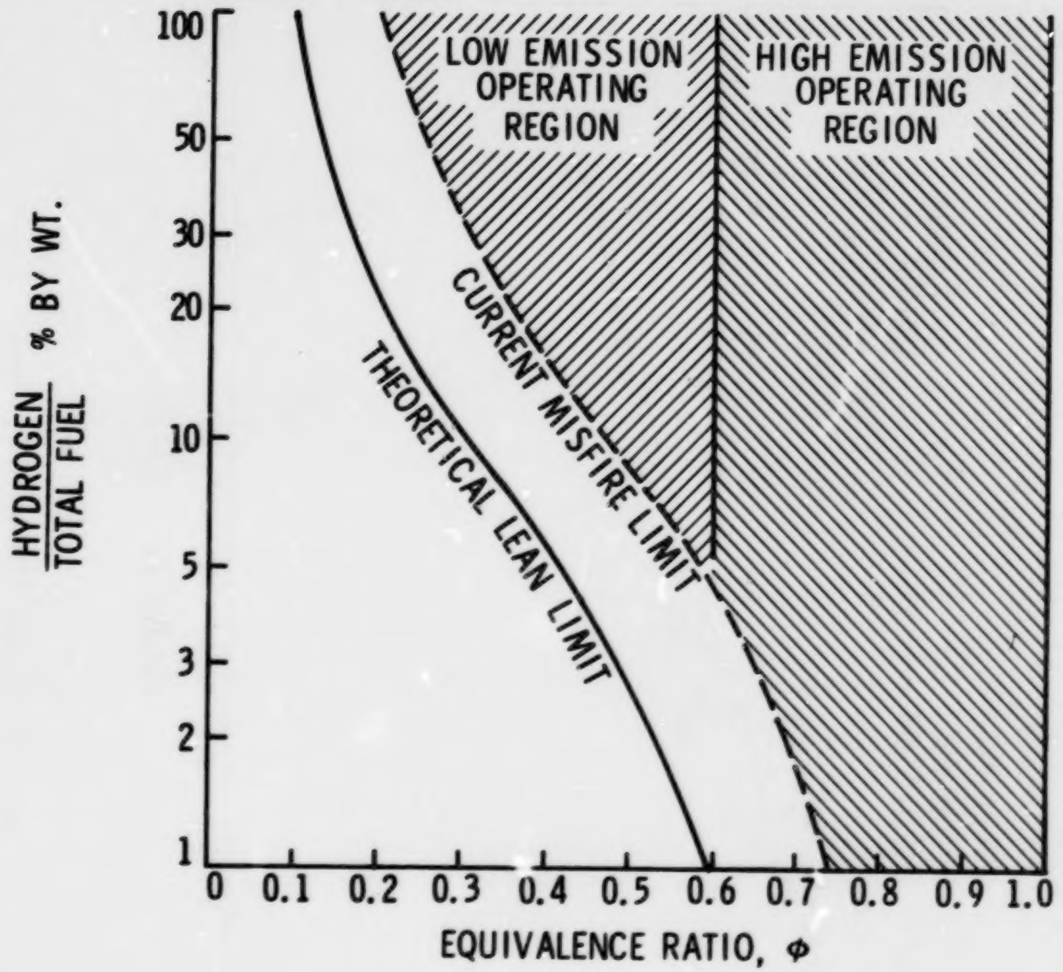


Fig. 171 Hydrogen Requirements

quantities of soot are produced. The current generator has a conversion efficiency of about 67%. Preliminary tests show engine operation with hydrogen generator products and gasoline is similar to operation with pure hydrogen and gasoline. The current experimental generator is 40 inches long and 8 inches in diameter. Composition measurements in various locations show the reactor volume is much larger than necessary. The next prototype generator (now being built) is 5 inches in diameter by 40 inches long.

The complete system will provide low-emission operation at high-efficiency, up to approximately 60% of full power. Full engine power remains available but with greater emissions and normal engine efficiency.

The actual gas mileage measured over the EPA Driving Cycle for the unmodified '73 Chevrolet Impala (350 engine) test car was 10 mi/gal. The predicted vehicle mileage with the current hydrogen generator, engine and induction system is 14 mi/gal for the same vehicle and driving cycle (about 75 HP at 2000 rpm, and 150 HP at 4500 rpm).

The experimental induction system has been removed from the dynamometer engine and is currently being mounted in the test car. For this first test car, hydrogen will be supplied from high-pressure cylinders mounted in the trunk. This car will be used to assess integration problems, emissions, fuel economy, and driveability. Later, a second vehicle will have a hydrogen generator installed for further testing.

The objective of the project is to develop a complete research vehicle which is self-contained and will meet the EPA 1977 Standards, while showing a significant gain in fuel economy.

The overall status of the JPL system is:

- V-8 engine tests show high efficiency, low NO_x and CO emissions.
- Hydrogen generation by partial oxidation has been demonstrated.
- V-8 engine operation on hydrogen generator products has been demonstrated.

Future plans include:

- Completing the bottled hydrogen car buildup and testing.
- Hydrogen generator car buildup and testing.
- Reduction of hydrocarbon emissions.
- Reduction in hydrogen generator size and complexity.

Current plans call for completion of the feasibility phase by December 15, 1973 and final project completion in December 1975.

Other areas of application for hydrogen injection include gas turbines, atmospheric pressure continuous combustors, and increasing the flammability of fuels for a wide range of engines.

Points Clarified during Question/Answer Period

- Tests show minimal effects from diluents that come out of the hydrogen generator (nitrogen, CO_2, and water) except for some power reduction from the displacement of oxygen by the inert diluents.
- Until water requirements of hydrogen generators are eliminated, about 25% of fuel load is required in water (for 24 gals. of fuel you need 6 gals. of water).
- The engine has not yet been operated in a vehicle; driveability tests have not been made. Predictions are that some peak power loss could occur. However at stoichiometric mixture ratios, hydrogen injection to decrease flammability limits, is not necessary.
- Hydrocarbon emissions need work. (They are about 4 to 10 times higher than standards) However, no work has been done in this direction yet. Some of the obvious steps to be considered include: greater turbulence in the combustion chamber, spark location and intensity, valve overlap to regulate residual gases in the combustion chamber, and addition of a thermal reactor.

- The basis for increasing thermal efficiency with decreasing equivalence ratio is that indicated efficiency more nearly approaches the ideal (about 55% for 8:1 compression ratio) with less dissociation and a polytropic expansion exponent close to that for air.
- Effect of temperature out of hydrogen generator has been explored only on a simulated basis so far. With good atomization and mixing, the effect of temperature should be small.
- Octane requirements for gasoline have not been explored. Experience shows no knock limitations at lean mixtures; hydrogen concentration at stoichiometric ratios is so small that no knocking occurs.
- The fuel supplied to the hydrogen generator was indolene-clear. It has low sulfur content. Sulfur is of concern regarding corrosion within the generator.
- For test purposes a pneumatic atomizer and an Autotronic (tuned cavity) atomizer were used to get small droplet sizes and even distribution. Carburetion was not used.
- Present hydrogen generator has been designed to deliver 3 lbs/hr of hydrogen. It looks like this will satisfy the driveability (acceleration) requirements.

B. Hydrogen Storage in Vehicles Using Metal Hydries, by Dr. Kenneth Hoffman, Brookhaven National Laboratory, Upton, New York

There is considerable interest (both short and long term) in hydrogen as a fuel because it has minimum pollution in its combustion products (H_2O and CO_2). Recent test of a hydrogen fueled engine in a vehicle showed NO_x of 0.2 grams/mile. It is also compatible with present (coal and nuclear) and long term (fusion, solar) domestically plentiful and replenishable primary energy sources.

Practical, safe, and economical methods of storing hydrogen on-board a vehicle are being sought. The present study was recently initiated to explore the possible use of metal hydrides as a means for doing this. Only thermally reversible systems are being considered. By supplying the heat of dissociation, the hydrogen is released for use in the engine. The basic metal is recharged over and over with hydrogen; it's only necessary to remove the heat of reaction. On a volume basis the hydrides store as much energy as liquid hydrogen. Solid hydrides have higher atom density than liquid hydrogen.

Figure 172 shows the pressure vs. composition isotherms in a typical hydrogen-metal system; Fig. 173 shows the dissociation pressures in hydrogen-metal systems. Figure 174 is a schematic of a possible metal hydride fuel system.

These materials seem to be safer than gasoline. They ignite and burn like coal if high enough temperatures are encountered. The magnesium system needs some special consideration.

To store 45 lbs of hydrogen (equivalent to 20 gallons of gasoline), the hydride storage bed would weigh about 700 lbs.

At this point a list of some 200 hydrides have been identified for screening. Criteria of comparison include: reversibility (want single step reactions) hydrogen content, P-T and heat of dissociation characteristics, safety, physical stablity (after numerous charge cycles), reaction stability (contaminants like water vapor and CO maybe a problem).

There is confidence that metal hydrides will be a safer, more convenient option over liquid hydrogen for those applications which require hydrogen fuel.

Points Clarified during Question/Answer Period

- The recharging cycle or reaction, when putting the hydrogen back into the hydride form, generates heat. For a magnesium hydride this is about 1/3 the heat of combustion; for iron or titanium hydrides, it is about 1/10 the heat of combustion. The charge time is limited by the ability to take that heat of

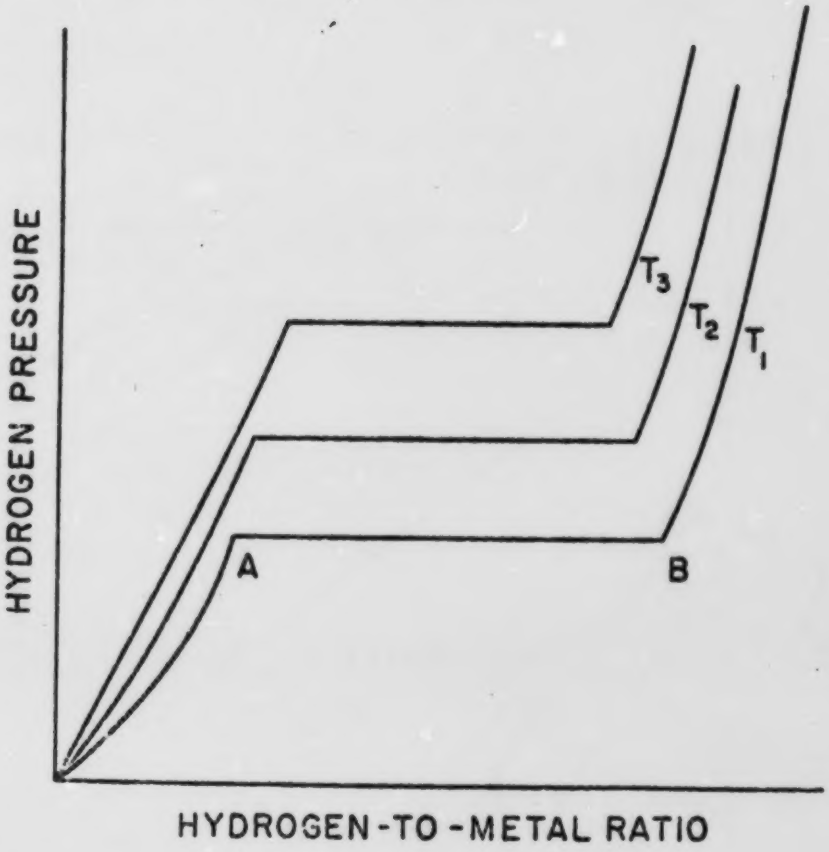


Fig. 172 Pressure Versus Composition Isotherms in a Typical Hydrogen-Metal System

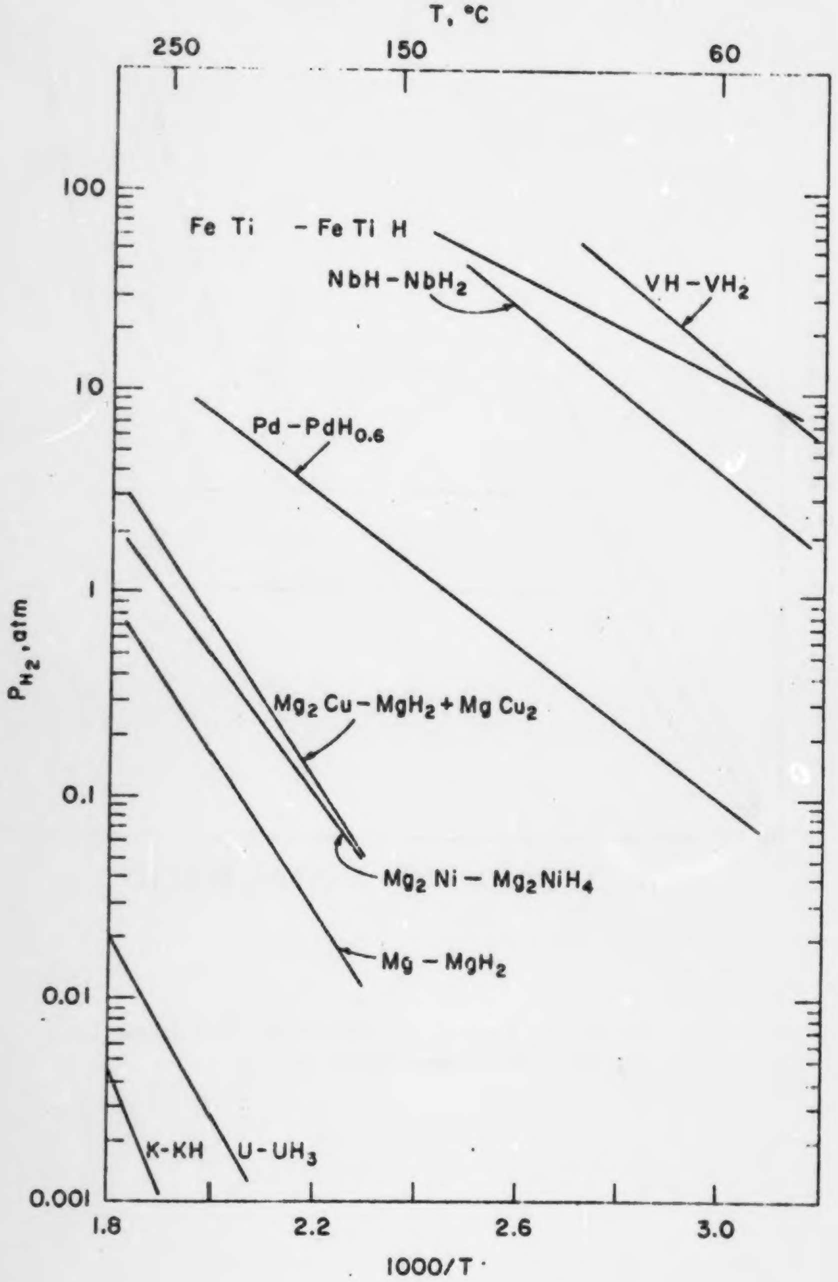


Fig. 173 Dissociation Pressures in Hydrogen-Metal Systems

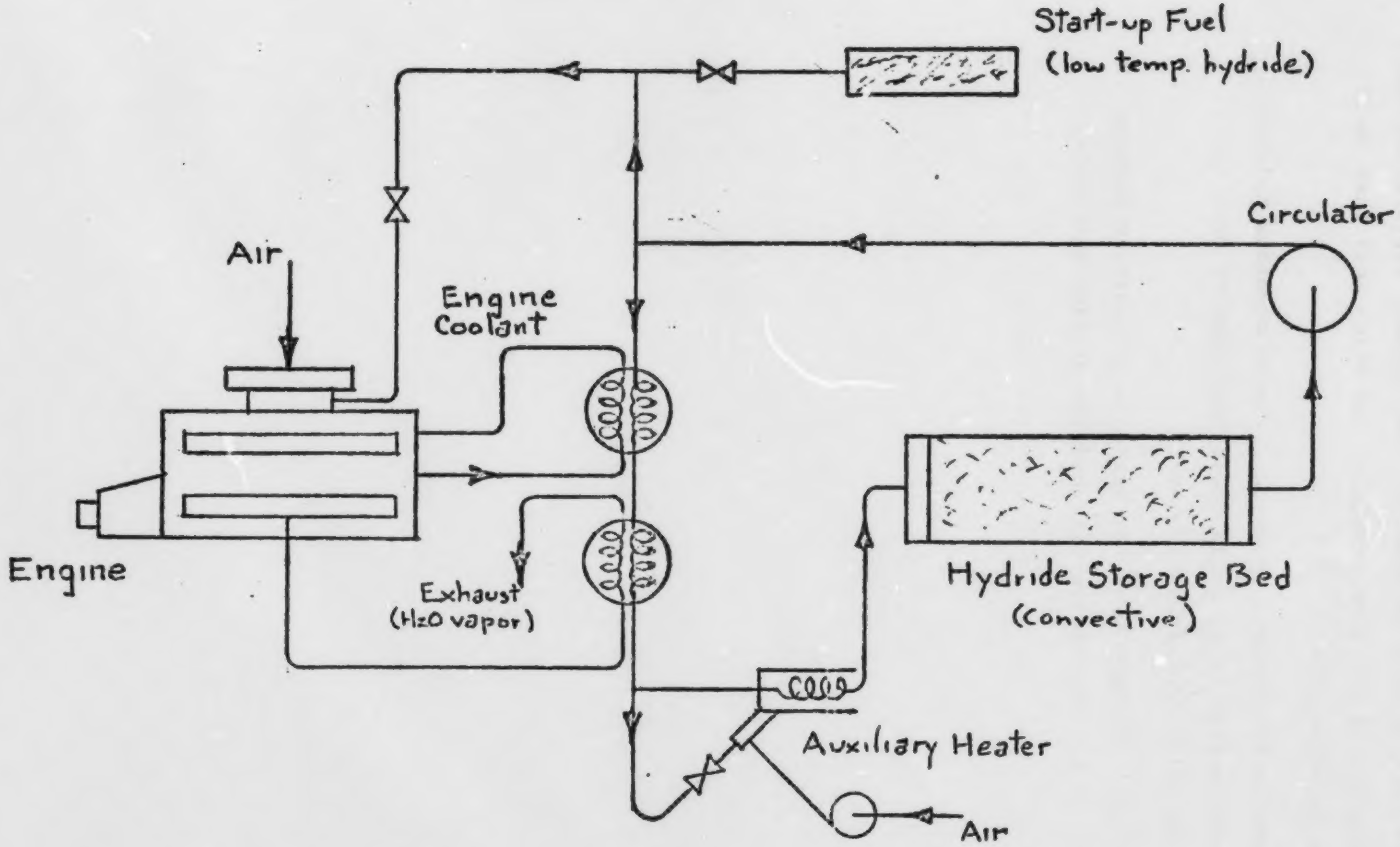

Start-up Fuel
(low temp. hydride)
Circulator
Air
Engine
Coolant
Engine
Exhaust
(H2O vapor)
Hydride Storage Bed
(Convective)
Auxiliary Heater
Air

Fig. 174 Automotive System Convective Hydride Storage Unit

reaction away. For the small beds tested to date, the recharge time has been about 5-10 minutes. The initial application under consideration is for fleet vehicles for which less than twenty minutes is estimated.

- Some speculative thought is being given to aluminum hydrides or ternary alloys which might offer improvements over the materials being considered to date.
- Interstitial hydrogen does not have enough hydrogen storage capacity to be competitive with hydride storage materials.

X. REDUCING FUEL CONSUMPTION FOR CURRENT AUTOMOBILES

In addition to the efforts toward new and alternative automotive power systems, there are numerous activities, both government and privately supported, aimed at improving current conventional automobiles. Two parallel studies supported by DOT and EPA, an in-house component study and vehicle tests by EPA, and a particular approach to improved fuel economy being pursued in England, are summarized here.

Of particular interest are the two parallel programs being supported by DOT and EPA to similar work statements by Arthur D. Little and Southwest Research Institute. The objective is to identify near term opportunities for reducing fuel consumption of conventional automobiles by as much as 30% if possible target. Such systems should be demonstrable by 1976 and should be reasonably able to be mass produced by 1980 (a million units per year). The results should help the government and the public to understand the critical issues.

Although the work statements of these concurrent programs are comparable, the emphasis is different. A. D. Little is emphasizing a thorough interface with industry and consultants; whereas, Southwest Research is focusing on independent fuel economy test and evaluation.

A. DOT/EPA Study, by Don Hurter, Project Manager, A. D. Little, Inc.

The following outline and charts summarize the approach, status, and results to date:

Goal: Identify and evaluate individual technological improvements of optimized automobile designs, incorporating fuel-conservation features for validation in vehicles in 1976.

Definitions and Constraints:

- A 30% reduction in fuel consumption is the target based on 1973 reference vehicles.
- Mature stage of development or using off-the-shelf hardware.

- No significant degradation of performance.
- No deviation from Federal Standards of safety, emissions, and noise.
- Minimal costs.
- Acceptability by public.

Approach:

- Characterize reference vehicles.
- Compile vehicle fuel usage and performance data from manufacturers (1973, 4200 lb standard car and a 3000 lb compact car).
- Identify improvements and obtain pertinent data.
- Verify improvements through contact with manufacturers and evaluation of their test and performance data.
- Simulate performance (of complete vehicle) through computer modeling.
- Based on technical analysis, evaluate potential of devices considered.
- Reject or initiate more thorough evaluation procedure.

Evaluation Factors:

Potential fuel usage and performance evaluation

- Fuel economy and emissions results
- Performance response
- Chance of success (stated or implied)
- Complexity

Cost and time considerations

- Initial cost estimate to implement modifications or new components
- Operating cost estimate
- Availability within timeframe of demonstration
- Time to implement into mass production schedule

Size and Weight

- Envelope size
- Weight

Operating considerations

- Durability
- Reliability and maintenance
- Compliance with constraints
- Potential for growth
- Effect on other subsystems

Automobile Manufacturers Contacted to Date:

- American Motors
- Chrysler Corporation
- General Motors
- Ford

Component Manufacturers and Related Industries Contacted to Date

Alcoa Aluminum
Autotronics Controls Corporation
Bendix Research Laboratories
Borg-Warner
Clark Equipment
McCulloch Corporation
Orshansky Transmission Corporation
Raytheon Company
Sundstrand Aviation
Teledyne Continental Motors
Texas Instruments
Tracor, Inc.
Universal Oil Products

A preliminary evaluation of the potential improvements to date are shown in Figs. 175 and 176.

Status of Program:

- Selected the reference vehicles.
- Conducted literature search and document review.
- Developed a data package and submitted it to major automobile manufacturers and component suppliers.
- Conducted interviews and field visits to collect performance and experimental data needed for the study.
- Analyzed experimental data received (in process).
- Analyzed driving modes (in process).

PRIME IMPROVEMENTS	IMPROVEMENTS BASED ON TANK MILEAGE	VEHICLE COST	EXCEPTIONS TO CONSTRAINTS	ADVANTAGES	DISADVANTAGES	CHANCE FOR SUCCESS
Diesel Designed Specifically For Passenger Cars	20-25%	First 5 years total cost up 10%	Earliest Production 1982	Fundamental Solution to Thermal Efficiency	Smoke and Odor	High Risk in Reducing Engine Weight
Optimally Match Conventional Engine with I.V. Transmission	10-15%	Estimate Equal to Present Auto	Earliest Production 1982	Fundamental Solution to Increasing Engine Load Factor	Harder to Meet Emissions--Very little Data Indicating Fuel Economy Gain for all Driving Conditions	High Risk 1. Benefits 2. Meeting Reliability and Durability Goals
Optimally Match Conventional Engine and 3-4 Speed Auto Transmission with Torque Converter Lock-up or Fluid Coupling	5-10%	Slightly More	Lock-up Converter & Fluid Coupling Produce Less Smooth Operation	Improving Existing Drive Train Efficiency with Proven Technology	Possible Lack of Customer Acceptance	Low Risk
Variable Intake Valve Lift Engine	5-10%	$25-50/Vehicle	None Known at This Time	Permits Consistent Combustion with Extremely Lean Air-Fuel Ratio at Part Throttle; i.e., 20:1-16:1	Added Controls and Valve Mechanism	Low Risk Prototype Available
High Intensity Ignition System	2-5%	$25-50/Vehicle	None Known at This Time	Permits Consistent Combustion with gain approximately one Air-Fuel Ratio	None	Very Low Risk
Fuel Injection with Feedback Control for Optimizing Air-Fuel Ratio	5-7%	$150-200/ Vehicle	None Known at This Time	Running Fuel Control at Optimum Air-Fuel Ratio	Cost, Durability & Complexity; Needs Development	High Risk Because of Trimming Control System & O_2 Sensor
Steel Belted Radial Vs. Fiberglass Belted Tires	3-5%	$20/Car	None	Improved Handling & Tire Life Additive to other Improvements	Harsher Ride	Very Low Risk
Aerodynamic Improvement in Frontal Area W/O Weight Change	4-5%	$20/Car	None	Fundamental Solution to Problem of Aerodynamic Drag	Could Result in Some Styling Compromise and Packaging Problems	Low Engineering Risk Possible High Customer Acceptance Risk
Drag 16-20%	5-8% 4-5%	$20/Car	None			
Dual Range Engine	10-15%	$50-100/Car	Possible Loss of Part Throttle Smoothness	Improves Efficiency at Less than 1/2 Throttle by Halving Working Capacity	Full Engine Development Required--Complicated Controls & Mechanism might present problem for straight 6	Intermediate Risk Little data on Performance
Weight 200-400 Lb. Reduction	2-8%	Depends on Material Choice Shouldn't be a cost penalty on Complete Redesign	None	Fundamental Approach to Problem Solution	Must go through Exhaustive Engineering Analysis & Design	Low Engineering Risk High Public Acceptance Risk

Fig. 175 Preliminary Evaluation of Potential Improvements

PRIME IMPROVEMENTS	IMPROVEMENTS BASED ON TANK MILEAGE	VEHICLE COST	EXCEPTIONS TO CONSTRAINTS	ADVANTAGES	DISADVANTAGES	CHANCE FOR SUCCESS
Standard Air-Conditioning With Constant Speed Drive or Improvement in Cycle	1-2%	$50/Car	None Known at This Time	Possible Reduction in Size, Weight, Power and Cost of Operation	Cost & Complexity Must be Developed	Intermediate Risk
Constant Speed Drive for Fan, Alternator & Power Steering	3-5%	$50/Car	None Known at This Time	Possible Reduction in Size, Weight, Power and Cost of Operation	Cost & Complexity Must be Developed	Intermediate Risk
Limited Fan Speed & Thermostatic Control	1-3%	$10/Car	None	Used only when required. Additive to all concepts	None	Now Available
Stratified Engines						
• Open Chamber	15-20%	$150/Car	Equality of Performance Unknown	Low Emissions & Improved Economy Multi-Fuel Capability	25 Years of Effort Have not made it work--Cost & Complexity	High Risk
• Pre-Chamber	Equal or Less	$125-150	Performance poor	Low Emissions	Engine not developed Low power Larger CID required	High Risk Data not complete Engine must be developed
Supercharger						
• Mechanical	≃ Equal	Double the Cost of Engine	Higher potential NO_x	High Power to Engine Weight	Poor Durability Complexity	No Gain
• Turbo	≃ Equal	$150-300	Hesitation very Difficult to Overcome	Part Throttle Economy Poor	Poor Durability Complexity	No Gain

Fig. 176 Preliminary Evaluation of Potential Improvements (Concluded)

- Evaluated subsystems and made final selection of innovative improvements.
- Processed data through computer simulation model to determine performances of vehicles and innovative devices (in process).

Points Clarified during Question/Answer Period

- The dual range concept involves a V-8 engine which operates on only four cylinders at light loads. Some work was done on this in the '40's and '50's. This is in the process of being traced.
- There is some controversey concerning the improvement, if any, in tank mileage derived from turbocharging.
- Until data are obtained on acceleration and performance of vehicles with stratified charge engines, judgment on viability of that type of engine is reserved.
- It was suggested that lubricant viscosity is a factor which can affect fuel economy.
- It was agreed at the outset of the program that not much effort would be devoted to the rotary engine because: detailed data needed for the program were still shrouded in secrecy and initial information showed the fuel consumption to be somewhat higher than conventional engines.

B. DOT/EPA Study by John W. Colburn, Project Manager, Southwest Research Institute

The objectives, definitions, and guidelines are essentially the same as those for A. D. Little. However, the reference vehicles for this study are:

Class I :	Ford Galaxie, Chevrolet Impala, Plymouth Fury (4300# curb weight)
Class II:	Ford Mustang, Chevrolet Camaro, Dodge Challenger (3300# curb weight)

Approach: Alternative vehicle designs will be synthesized and evaluated to determine not only the fuel consumption reductions possible, but the potential effects on purchase costs, operating characteristics, maintenance costs, and consumer acceptance. Changes to current automotive designs are being considered in typical areas such as engines, transmissions, accessory loads and drive methods, tire rolling resistance, and aerodynamic resistance.

A series of tests are being conducted to assess the power requirements vs. fuel consumption characteristics of the reference vehicles. Simultaneously, general consideration is being given to the potential [illegible] various design changes. Upon completion of the baseline testing, the [illegible] will be reviewed for potential areas of fuel use improvements.

Test Program Description and Status: Multiple road tests are conducted on each vehicle to accurately determine road load fuel consumption at 20, 30, 40, 50, 60, and 70 mph, with and without air conditioning. In addition to fuel consumption data, engine speed, vacuum, propshaft torque and propshaft speed are recorded. Limited performance data are also acquired. These tests are complete on five of the vehicles.

All engine accessories and auxiliaries are belt driven by a cradled electric motor to determine load/speed requirements. These tests are complete.

Six LA-4 driving cycles (23 minutes each) are run on each vehicle on chassis dynamometer tests. The first sequence is: Cold start - hot start - hot start. The second sequency is: Cold start - hot start (A/C on) - hot start (A/C on). Engine vacuum, engine speed, propshaft speed, propshaft torque, and cummulative fuel consumed are recorded continuously during each test. These tests are complete on three of the vehicles.

Engine power/BSFC tests are planned on four engines. The vehicle is positioned on a rack and the transmission is removed. A flywheel is installed and the engine is then coupled to a dynamometer. Fuel consumption at varied loads and speeds is obtained to provide a partial engine performance map. Tests on one vehicle have been completed.

The remaining testing will be completed by the end of October with the exception of one power/BSFC test which is scheduled for completion by 9 November.

Points Clarified during Question/Answer Period

- The engine performance tests are being run in the car mainly for cost reasons.

C. EPA In-House Component Improvement Study, by T. M. Sebestyen, Head, Gas Turbine Section, Alternative Automotive Power Systems Division

Early in 1972 the Alternative Automotive Power Systems Division performed a cursory study on the fuel economy of the conventional American family car. The purpose of the study was to pinpoint those areas most desirable for improvement, and through them offer a much needed and early impact on the fuel consumed by the car population in the United States.

The study showed a definite potential for improvement, although not without trade-offs; all well known in the automobile industry.

Highlights of the study are summarized as part of a governmental effort now underway to inform the public and generate action.

The baseline for the study is the 1972 American family car described as follows:

Weight	4300 lb (1950kg)
Engine Size	350 in^3 (5.74 ℓ)
Transmission	Automatic
FDC Fuel Economy	12.5 mi/g (18.8 ℓ/100km)
CDC (Composite Driving Cycle - Avg. Speed 50 mph) Fuel Economy	14.8 mi/g (15.9 ℓ/100km)

The items listed below were considered potential improvements, assumptions and possible gain to be expected in fuel economy are also shown. It should be noted, however, that these improvements are not additive; all add to the cost of the baseline car; some might increase emissions (compression ratio has not been listed), and some might involve other trade-offs such as engine life, driveability, etc.:

Item	Improvement Through	Assumptions	Projected Fuel Economy Gain
Carburetion	•Atomization •Mixing •Warm-Up	Successful Lean Cold Starts	FDC(at 50°F) 15% CDC(at 0° F) 30%
Fuel Injection	•No Intake Heat Mixing •No Decel. Fuel	Low Emissions Maintained	FDC 15% CDC 15%
Ignition	•Spark Energy •Spark Duration	Complete Burning of Lean Mixtures	FDC 5% CDC 3%
Stratification	•No Throttling •Comp. Ratio •Lean Mixture	Low Emissions Maintained	FDC 30% CDC 20%
Engine Friction	•Design	Performance & Life Maintained	FDC 4% CDC 6%
Exhaust Loss	•Variable Geometry	Silencing Maintained	FDC 2% CDC 4%
Accessories (See Fig. 177)	•Constant Speed Drive	Full Performance Near Idle	FDC 10% CDC 8%
Rankine APU	•Constant Speed Accessory Drive •Heat Recovery	Rankine Boiler Acts as a Reactor	FDC 0% CDC 7%
Turbocharging	•Displacement	Max. Power Maintained *Minor Reduction in Compression Ratio	FDC *15% CDC *12%
Variable Displacement	•Load Matching	Emissions Unaffected	FDC 60% CDC 60%
Regenerative Braking	•Recovering Kinetic Energy	50% of Energy Available 40% Loop Efficiency	FDC 5% CDC 2%
Transmission Modifications	•Torque Converter Lock-Up	Lock-up in 2nd Gear. Good Shift Quality	FDC 10% CDC 8%
Infinitely Variable Transmission (See Fig. 178)	•Optimum Engine Operation •Efficiency	Traction Device High Efficiency at Low Load and Speed	FDC >20% CDC 20%

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*Up-Dated 11/8/73

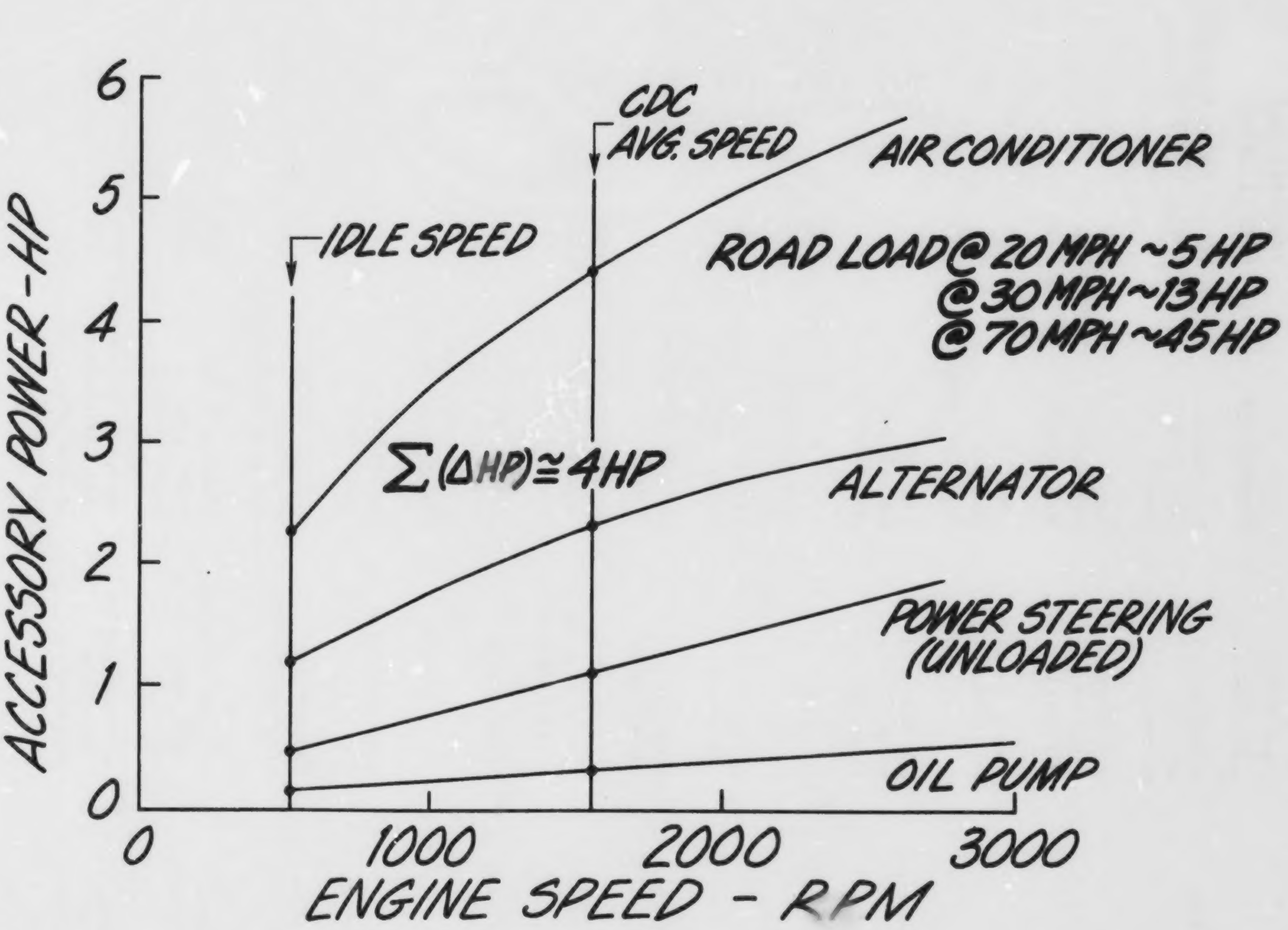

Fig. 177 The Potential Fuel Saving with Constant-Speed Accessories

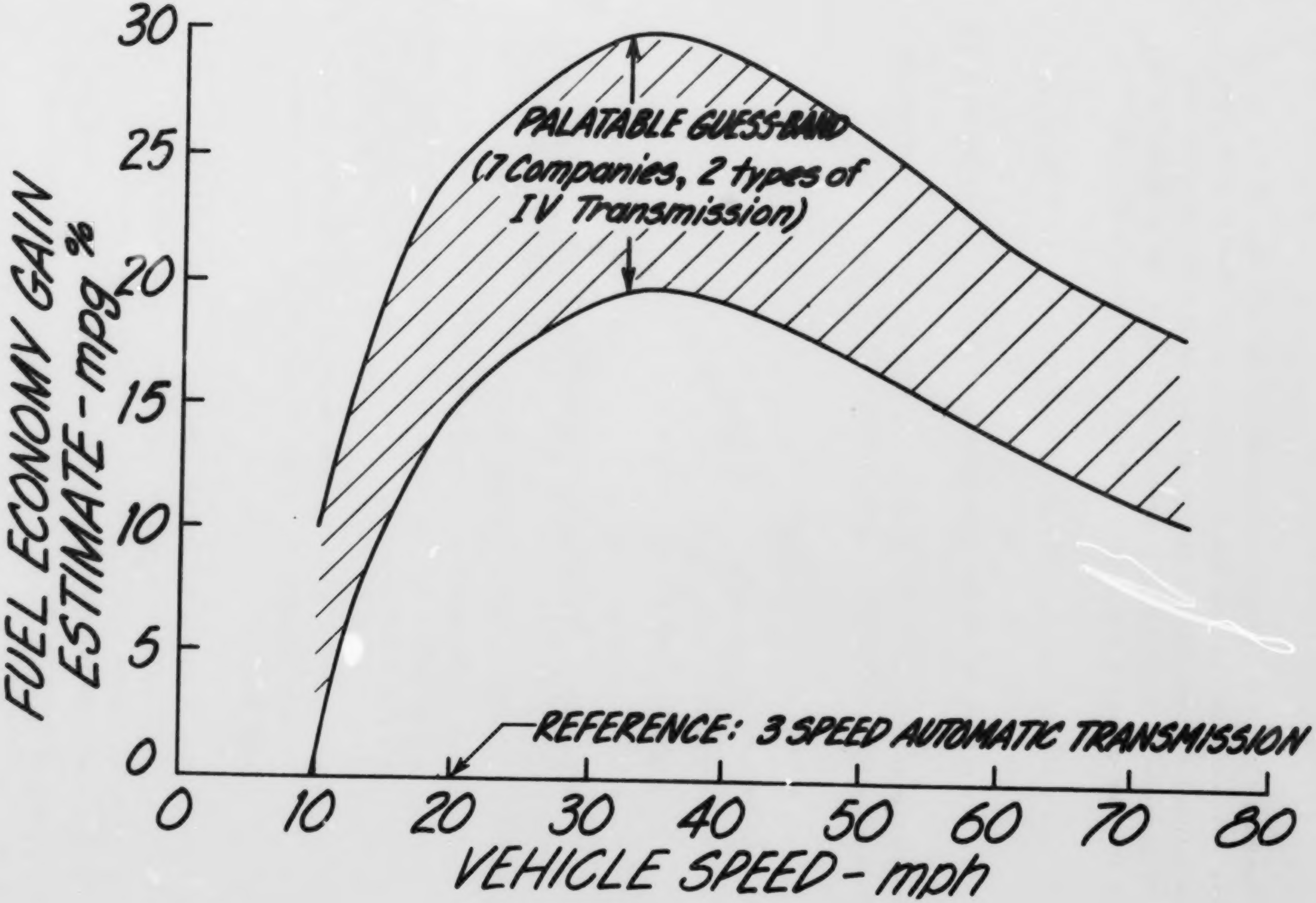

Fig. 178 The Potential Fuel Saving with Infinitely Variable Transmission

Although all of these improvements will add to the first cost of the vehicle, they still can have important impact on the car owner finances as well as the national economy. For example, a car equipped with an infinitely variable transmission instead of a 3-speed automatic might cost an extra $66.00 but increase the miles per gallon by 20%. The benefits from this are:

• reduced fuel cost over the life of the car (at 14 mpg; 40¢ per gallon)	$600
• car population fuel consumption reduced	14 billion gal/yr

Considering the results of this study, it is believed that more research and development furds could be fruitfully invested in:

- Fuel-air mixture preparation
- Ignition
- Stratification
- Turbocharging
- Torque converter lock-up
- Infinitely variable drives - low power and high power

Points Clarified during Question/Answer Period

- The I-V transmission information is based on results of recent studies by MTI and Sundstrand, which recommended hydromechanical and traction types.

- More accurate terminology was suggested, i.e. use "continuously" variable transmission instead of "infinitely" variable transmission.

- This study did not consider the other benefits reflected in the vehicle stemming from the powerplant improvements, such as lighter materials, brakes, and other items having to do with the behicle itself and its running gear rather than just the engine.

- A continuously variable transmission may also affect the service life of the engine.
- It is believed that the CDC (Composite Driving Cycle) reflects the average usage of the vehicle.

D. EPA Fuel Economy Data from 1973 and 1974 Model Year Vehicles, by Dave Kimball, Project Engineer, Certification and Surveillance Division

On September 18, 1973, EPA released fuel economy data from 1974 model year vehicles which had been tested by EPA to insure compliance with Federal Emission Standards. The fuel economy values were calcuated using exhaust emission test results (See Fig. 179).

The basic assumptions used for the carbon balance method for calculating the fuel economy are:

- The only source of carbon entering the engine is fuel.
- All of the carbon leaving the engine is measured as HC, CO, or CO_2.
- There are no fuel or carbon leaks (carbon in = carbon out).

Over 285 correlation tests were run to establish the validity of this method of determining fuel consumption as compared to weighing techniques. It was found that the carbon balance methods gave average fuel economy values 4% higher than the weigh methods. The difference is believed to be accounted for by fuel evaporation losses. Thus, the fuel economy data are based on the emissions measured over the Federal Driving Cycle according to Federal Test Procedures.

A comparison of the national average fuel economy data from DOT and EPA for both calendar and model years since 1966 are shown in Fig. 180. The data for 1974 model year cars (390 test vehicles) are shown in Fig. 181. A comparison of the same data with 1973 model year is shown in Fig. 182. If the same weight distribution is assumed for 1973 and 1974 as in 1972, (weight

$$\text{Fuel Economy (mpg)} = \frac{\overset{\text{carbon weight fraction 1/ of gasoline}\ \downarrow}{0.866}\left(\frac{\text{gm. carbon}}{\text{gm. gasoline}}\right) \times \overset{\downarrow\ \text{density of gasoline 2/}}{6.167}\left(\frac{\text{lb. gasoline}}{\text{gallon gasoline}}\right) \times 453.6\left(\frac{\text{gm. gasoline}}{\text{lb. gasoline}}\right)}{\underset{\uparrow\ \text{carbon weight fraction of hydrocarbons in exhaust 3/}}{0.866}\left(\frac{\text{gm carbon}}{\text{gm. HC}}\right) \times \underset{\uparrow\ \text{measured HC mass emissions per mile traveled}}{HC}\left(\frac{\text{gm HC}}{\text{mile}}\right) + \underset{\uparrow\ \text{carbon weight fraction of CO in exhaust}}{0.429}\left(\frac{\text{gm carbon}}{\text{gm CO}}\right) \times \underset{\uparrow\ \text{measured CO mass emissions per mile traveled}}{CO}\left(\frac{\text{gm CO}}{\text{mile}}\right) + \underset{\uparrow\ \text{carbon weight fraction of } CO_2 \text{ in exhaust}}{0.273}\left(\frac{\text{gm carbon}}{\text{gm } CO_2}\right) \times \underset{\uparrow\ \text{measured } CO_2 \text{ mass emissions per mile traveled}}{CO_2}\left(\frac{\text{gm } CO_2}{\text{mile}}\right)}$$

$$= \frac{0.866 \times 6.167 \times 453.6 \ \left(\frac{\text{gm. carbon}}{\text{gallon gasoline}}\right)}{0.866 \times HC + 0.429 \times CO + 0.273 \times CO_2 \left(\frac{\text{gm. carbon}}{\text{mile}}\right)}$$

$$\text{Fuel Economy} = \frac{2423}{0.866 \times HC + 0.429 \times CO + 0.273 \times CO_2}\left(\frac{\text{mile}}{\text{gallon}}\right)$$

1/ Based on "gasoline" with carbon-hydrogen ratio of $CH_{1.85}$

2/ Density based upon mean API specific gravity specification of Indolene 30

3/ Assuming that hydrocarbons in the exhaust are essentially unburned gasoline and hence would also be of carbon-hydrogen ratio of $CH_{1.85}$.

Fig. 179 Derivation of Expression to Calculate Fuel Economy from Exhaust Emission Test Results

⊙ DOT data

△ Data computed using carbon-balance, FTP technique from Austin and Hellman SAE paper # 730790, Passenger Car Fuel Economy- Trends and Influencing Factors

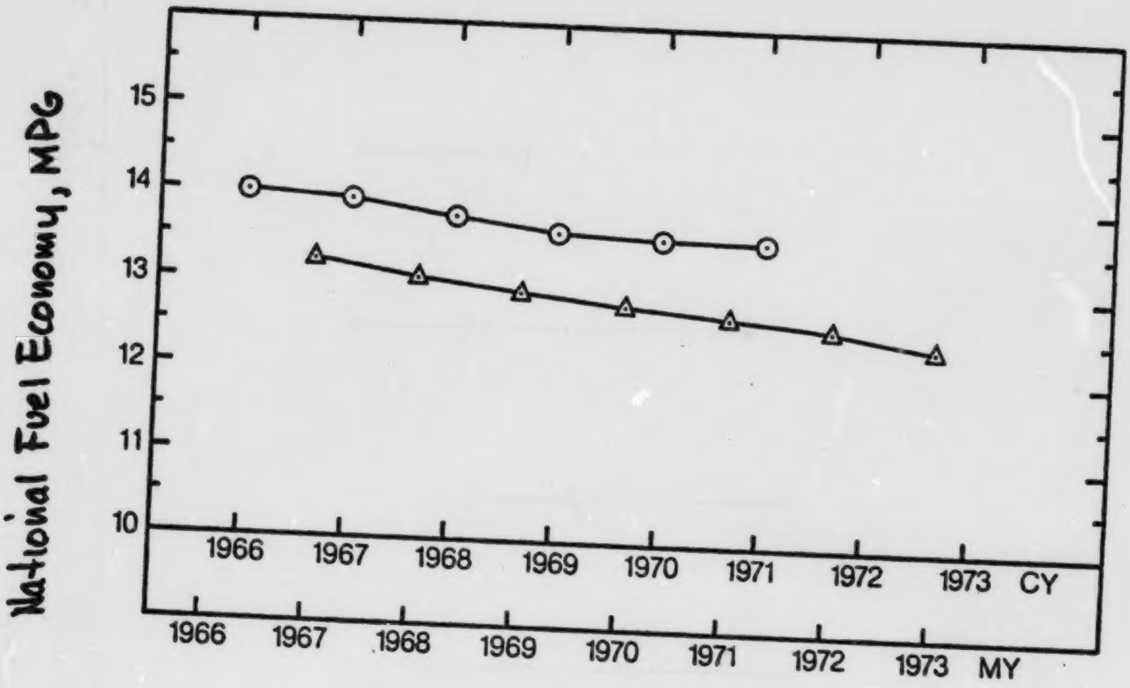

Fig. 180 National Average Fuel Economy

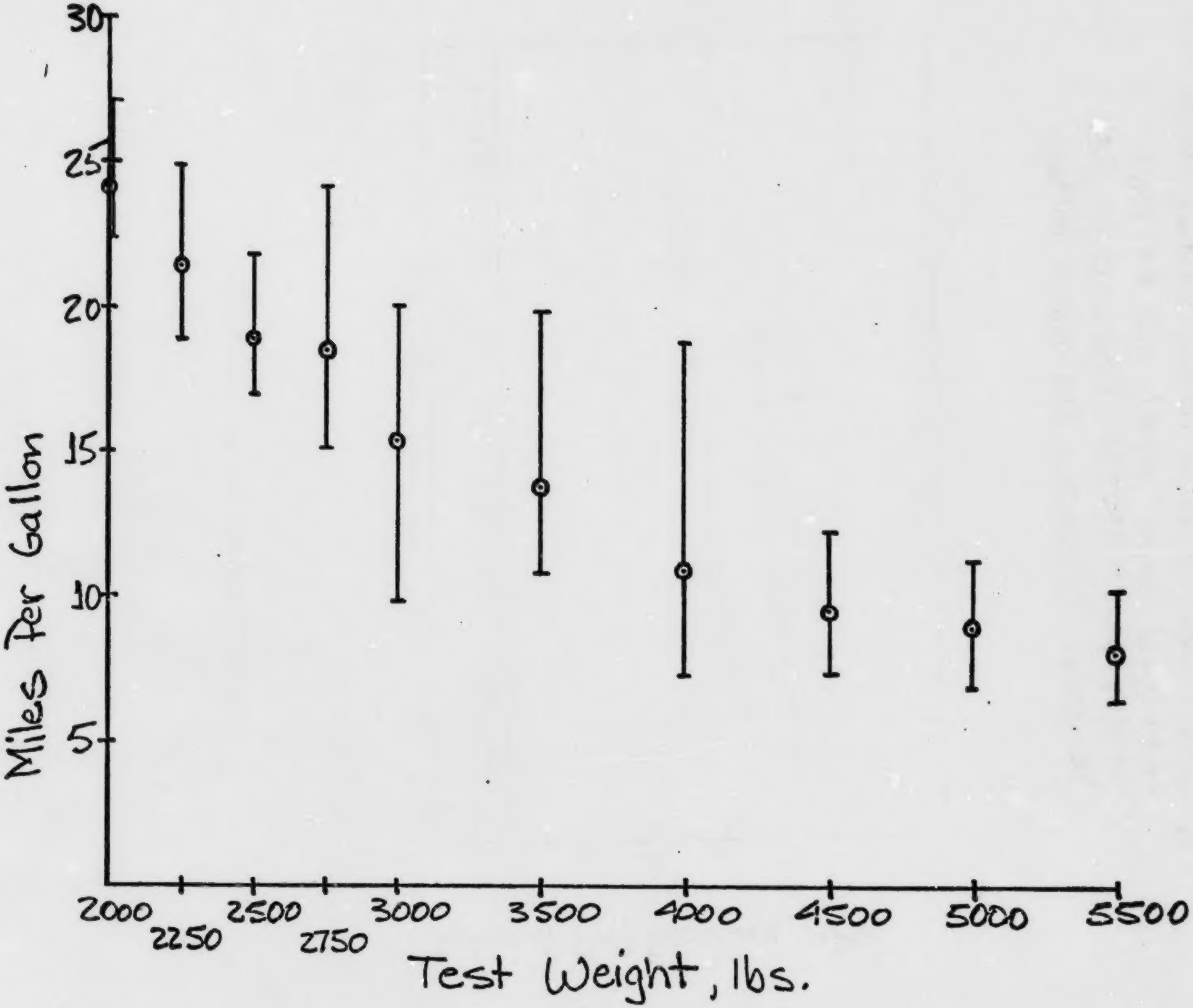

Fig. 181 Fuel Economy of Certified 1974 Model Year Vehicles

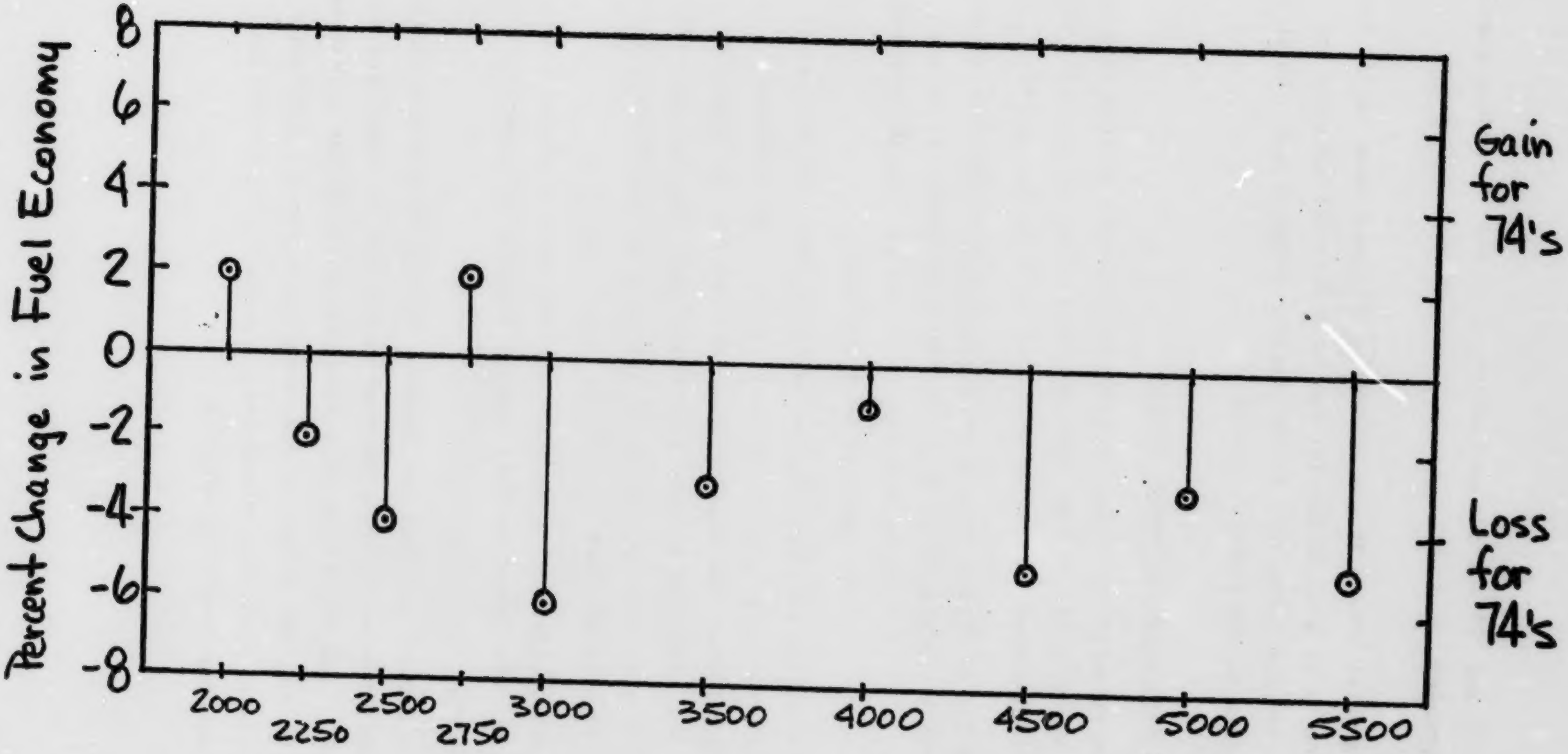

Fig. 182 Percent Change in Fuel Economy Between 1973 and 1974 Model Year Vehicles

distribution data '73 and '74 not yet available), then the '74 models show a 3% fuel economy penalty.

Two counteracting general trends in the automobile business were noted. The same model cars seem to be getting heavier due to safety requirements and accessories; more cars are being sold in the smaller weight class. Which of these will dominate is not known at present.

Points Clarified during Question/Answer Period

- Data on variability of fuel economy on a given car from test to test, and from lab to lab, were not presented. In general, such test results were considered good and suitably consistent.
- The factor of "mpg x vehicle weight = constant" was discussed. It seems to be a good correlating factor; however, it must be used with caution since some other factors such as performance level of the vehicle may also be significant.
- The philosophy and criteria for selecting vehicles for certification tests is complex; however, some of the elements considered are: the high selling vehicles and the vehicles which are suspected to have high emissions. The law says all vehicles must qualify. Then, if the most difficult ones qualify, the others should have no problem.
- Fuel economy data are presently released on a voluntary basis. How long this Voluntary Fuel Economy Program will continue is not known.
- It was pointed out that the Federal Driving Cycle and Procedures are not universally accepted even within EPA for measuring fuel economy. But FDC is the only procedure that EPA has authorization to run, and it has no statutory authority or legislation on which to proscribe procedures to characterize or control fuel economy levels in vehicles.

E. Potential of Heat Pipe for Near Term Reduced Fuel Consumption and Pollution, by Roger Lindsay, Shell International and Dr. John L. Wilson, National Engineering Laboratory, Department of Trade and Industry, London, England

The precise definition of a heat pipe is a self-contained boiling-condensing system in which the condensate is pumped from condenser to boiler under the action of capillary forces. A typical layout of a heat pipe is shown in Fig. 183.

The device has a number of unique characteristics which make it an appropriate means of transferring exhaust heat to vaporize gasoline. It has an effective thermal conductivity 500 or more times that of copper. The condenser, where heat is given up, is at a uniform temperature selected to be high enough to ensure complete evaporation of the fuel, but low enough to avoid fuel cracking and deposition. The device acts as a heat flux or area transformer; the surface area required to pick up heat from the exhaust is of necessity large due to the relatively poor heat transfer rate attainable from the exhaust gases, while the surface area used to vaporize the fuel can be small ensuring low fuel accumulation in the vaporizing section, an important point in obtaining the high response necessary to give good driveability. Lastly, there is a "gas control" method of regulating the temperature of the fuel vaporizing surface described below.

In some versions the "Vapipe" is located as shown in Fig. 184. Heat is transferred from the exhaust gases to the heat pipe fluid at the boiler, the vapor flowing through a vertical inter-connecting tube to the fuel vaporizing section where the heat pipe vapor condenses, giving up its latent heat to the vaporizing fuel. Above the vaporizing section is the gas control.

The vaporizing section is immediately downstream of a conventional carburetor as shown schematically in Fig. 185. The arrangement of the vaporizer is essentially that of a small tubular heat exchanger, the air-fuel mixture flowing on the outside of the tubes or on the shell-side as it is called. The heat pipe fluid condenses on the inside of the tubes. The mixture

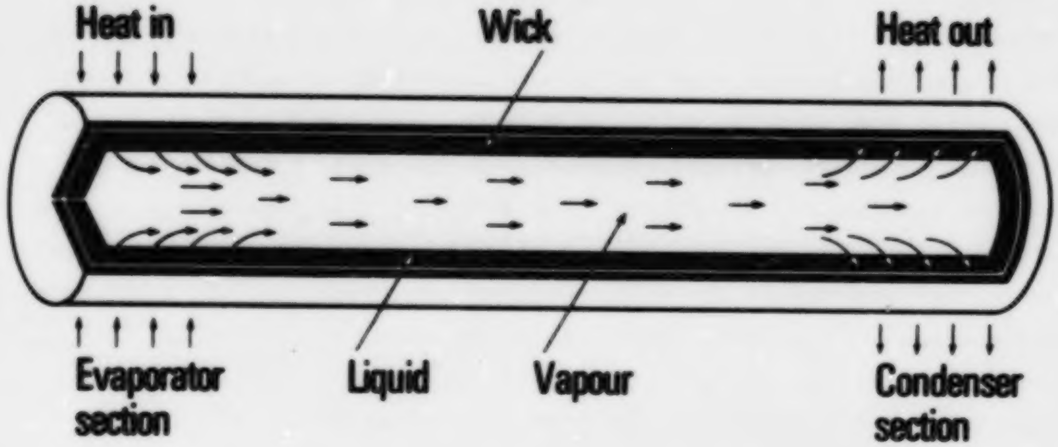
Heat in
Wick
Heat out
Evaporator section
Liquid
Vapour
Condenser section

Fig. 183 A Heat Pipe

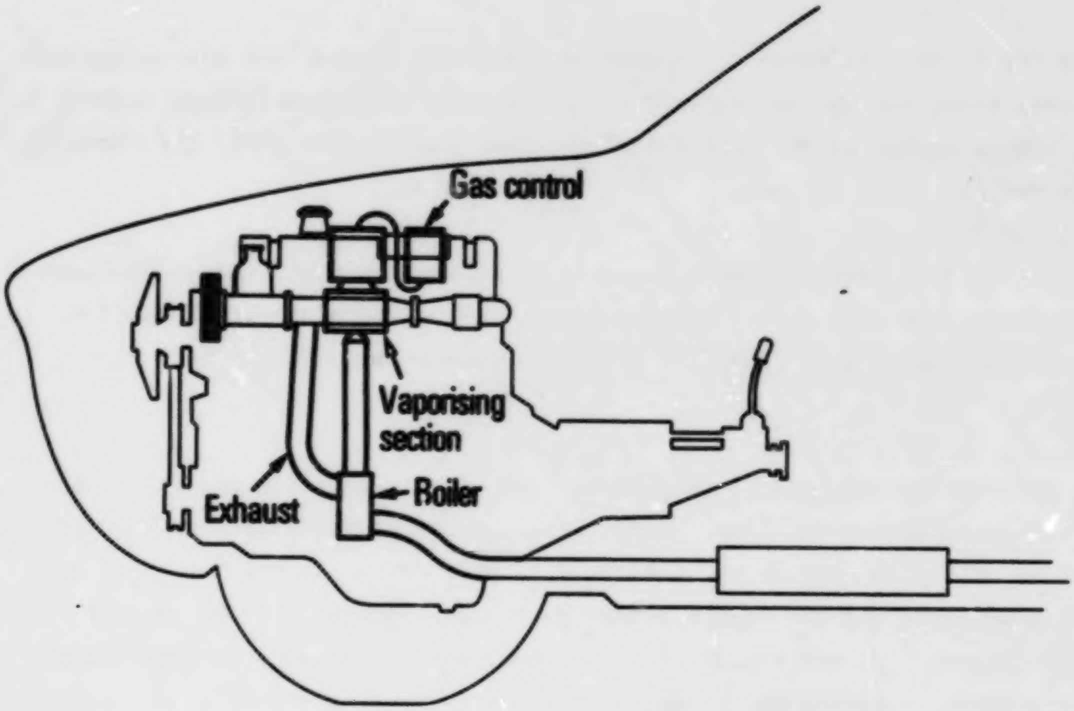
Gas control
Vaporising section
Exhaust
Boiler

Fig. 184 Location of Vapipe

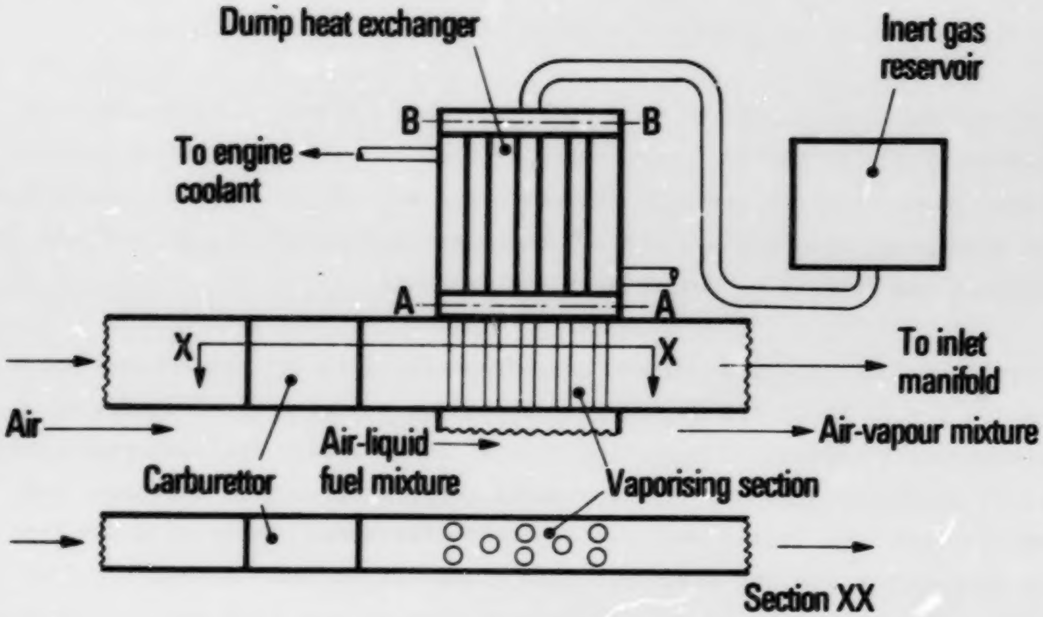
Dump heat exchanger
Inert gas reservoir
B
B
To engine coolant
A
A
X
X
To inlet manifold
Air
Air-liquid fuel mixture
Air-vapour mixture
Carburettor
Vaporising section
Section XX

Fig. 185 Vaporizing Section and Gas Control System

velocity is kept sufficiently high to prevent the liquid fuel separating and flowing along the bottom of the duct; it is also sufficiently high to keep the liquid layers on the heated surface thin, and to give good mass transfer from the liquid to the vapor.

In its simplest form the boiler is what is known as a "tube and jacket" heat exchanger. The heat pipe liquid is boiled inside the heat pipe, heated by the exhaust gases which flow in an annular passage outside the heat pipe wall.

The gas control consists of two parts; a dump heat exchanger and a gas reservoir as shown in Fig. 185. Sufficient gas is put into the heat pipe so that at idling the gas-vapor interface is at Section AA; the motion of the heat pipe vapor up the Vapipe separates the gas vapor. As the exhaust gases increase in temperature the heat pipe vapor increases in temperature and pressure, compressing the gases until at the maximum exhaust gas temperature the gas-vapor interface is at Section BB. The dump heat exchanger now contains vapor which is condensed by water from the main automobile cooling system absorbing the heat not required at the vaporizing section. The system can be designed to maintain a relatively constant temperature at the vaporizing section over the whole range of exhaust gas temperatures.

An alternate form of control uses an exhaust gas by-pass to the boiler. A pressure switch in the Vapipe actuates a solenoid operated valve to by-pass exhaust gases when the pressure exceeds a pre-set value. This is considered less attractive than the gas control technique due to well-known problems of corrosion and seizure of moving parts in exhausts.

Vapipes have been constructed and tested operating in the temperature range from 100°C (212°F) to 220°C (428°F). Depending on the desired operating temperature, a variety of heat-pipe fluids can be used. The heat-pipe fluid must be thermally stable at the operating temperature and in addition, low viscosity and high latent heat are desirable features. Increasing the heat pipe temperature has the advantage that a smaller surface is then required for the vaporizing section and thus a more compact unit with smaller pressure drop can be obtained; a smaller dump heat exchanger is then also required.

The vaporizing section increases the temperature of the charge to the engine, but this can be alleviated by by-passing a portion of the air to the inlet manifold. Typical tests with a 1.8 litre engine running at full throttle with a by-pass system showed that about 2.5 kw of heat was required for fuel evaporation giving a mixture temperature of $40^{\circ}C$ at the inlet manifold; 80 per cent of the air was by-passed in this system.

Experience regarding long term operational behavior of these units is limited. Prototype models have about a year of operational experience.

Even with lean carburetion the Vapipe will enable the automobile to be started by conventional means using a choke. Existing designs of Vapipe can be brought to full operating temperature within a minute from $0^{\circ}C$ ($32^{\circ}F$) and with further development improvement on this will be possible. Auxiliary heating may be used to minimize cold-start enrichment.

Some performance data are summarized in Fig. 186. These show the advantage obtained from the homogeneous charge arising from the formation of a vapor air mixture downstream of the carburetor.

Points Clarified during Question/Answer Period

- The heat pipe could also work with inlet below the exhaust if it was necessary. Some question was raised relative to the terminology since the Vapipe system looks like a reflux condenser with a gravity return.
- The possible use of an ultra-sonic atomization device for warm-up was suggested.
- Power losses are encountered due to elevated inlet temperatures (perhaps 15% due to reduced volumetric efficiency) pressure losses, and lean mixtures. Subsequent designs will minimize these losses.

Test procedure	Legislative limit			Standard car Standard setting			Vapipe car Standard setting			Vapipe car Lean setting		
	HC	CO	NO_x	HC	CO	NO_x	HC	CO	NO_x	HC	CO	NO_x
European ECE Type 15 test gm/test	9.4	134	-	2.8	88.0	12.9	2.0	66.4	15.4	3.7	31.5	10.5
Fuel consumption miles per Imperial Gallon (miles per U.S. Gallon)		-			14.6	(12.2)		18.0	(15.0)		17.4	(14.5)
Japanese 10 mode test gm/km	3.8	26	3.0	1.7	22.8	2.6	1.2	19.8	2.9	1.2	2.1	3.1
Fuel consumption miles per Imperial Gallon (miles per U.S. Gallon)		-			16.5	(13.8)		20.4	(17.0)		22.8	(19.0)
1973 U.S. Federal Test gm/mile	3.4	39	3.0	2.3	18.3	5.6	1.6	21.1	3.8	1.7	5.9	4.5
Fuel consumption miles per Imperial Gallon (miles per U.S. Gallon)		-			20.3	(16.9)		27.2	(22.7)		29.0	(24.2)
1975 U.S. Federal Test gm/mile	1.5	15	3.1	2.2	16.4	5.4	1.5	18.8	3.7	1.5	3.7	4.6
Fuel consumption miles per Imperial Gallon (miles per U.S. Gallon)		-			20.3	(16.9)		27.2	(22.7)		29.0	(24.2)

Fig. 186 Exhaust Emissions and Fuel Consumption Over Various Test Cycles With and Without Vapipe

- In addition to maximum power limitations, other problems with this system include: practical manufacturing techniques, and practical cold start emission controls.
- Actual surface temperatures encountered in the vapour generator were not readily available. They are maintained constant within about 20°C over the operating range.

XI. LEAD PARTICULATES IN THE EXHAUST

A. Exhaust Filter Systems for the Removal of Particulate Lead, by S. Wallin, Principal Scientific Officer, Warren Springs Laboratory, Department of Trade and Industry, London, England

A five-part program of work is currently being carried out in the U.K. by the Motor Industries Research Laboratories and Transport Road Research Laboratory to evaluate lead-trap exhaust filters for petrol-engined vehicles. Road-vehicle tests are being made on twenty vehicles to obtain an 'in-service' assessment of the lead filter. A laboratory series of life and performance tests has been initiated. An engine dynamometer is used for the evaluation of the lead filter as related to the vehicle road conditions.

Basic studies to understand the mode of operation of the lead filter indicate the effect of path length, gas velocity and temperature. X-ray diffraction results show that during, or after, the lead trapping process the lead halides react with the sulphur dioxide to give lead sulphate. Further work on the basic studies is continuing.

Screening tests were carried out to study the filter performance with variations in fuel composition and operating temperature. The effect of reducing the lead content of the fuel produced a lower filter efficiency; replacement of lead by aromatic constituents also produced a lower filter efficiency.

Questions: None

B. On-Line Monitoring of Lead Emissions from Motor Vehicles, by S. Wallin (See Above)

This work is also being carried out in the U.K. by the Motor Industries Research Laboratories and the Transport Research Laboratory.

A commercially available, portable atomic absorption spectrophotomer was modified to give a linear output which could be measured using a recorder or integrator.

The monitoring system involves diluting the exhaust gases to achieve isokinetic sampling at an acceptable lead concentration for the atomic absorption instrument. Calibration tests showed that the instrument could be used over a range of 0-40 mg/m^3 of lead in the diluted gas. This is equivalent to approximately 0-1000 mg/m^3 in the exhaust gas.

The system has been used to obtain information on lead emissions from vehicles for different driving situations and patterns. Continuous on-line monitoring of lead emissions from vehicles fitted with exhaust filter devices has been used for test distances up to 120 miles. Figures 187 and 188 show the concentrations of lead detected in the dilution system on the same section of road for 1.3-litre and 3.0-litre vehicles respectively. It is planned to compare lead emissions (for different driving conditions) from vehicles with lead filters with those having conventional silencer systems.

Points Clarified during Question/Answer Period

- Although particle sizes change with engine operating conditions, the use of a centrifugal fan breaks up most of the particles; the isokinetic sampling techniques are believed to give a satisfactorily porportional sample of the particulates.
- Knowing the gas velocity and temperature of the gas, it is possible to get the mass emission as well as the concentration, such as shown in Fig. 187.

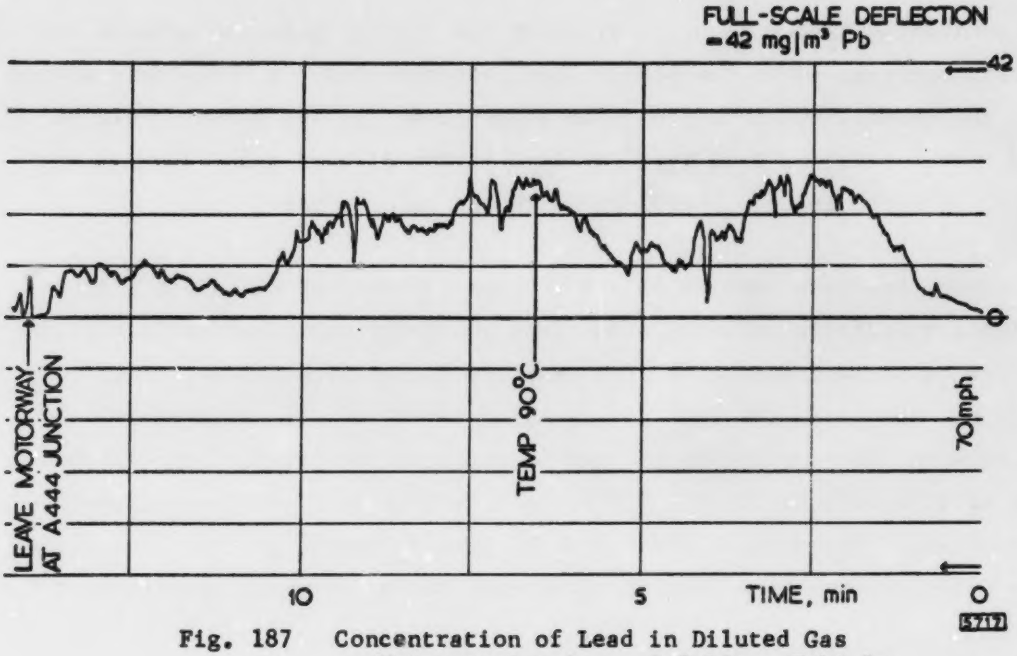

Fig. 187 Concentration of Lead in Diluted Gas on Motorway Section — 1.3 Liter Vehicle

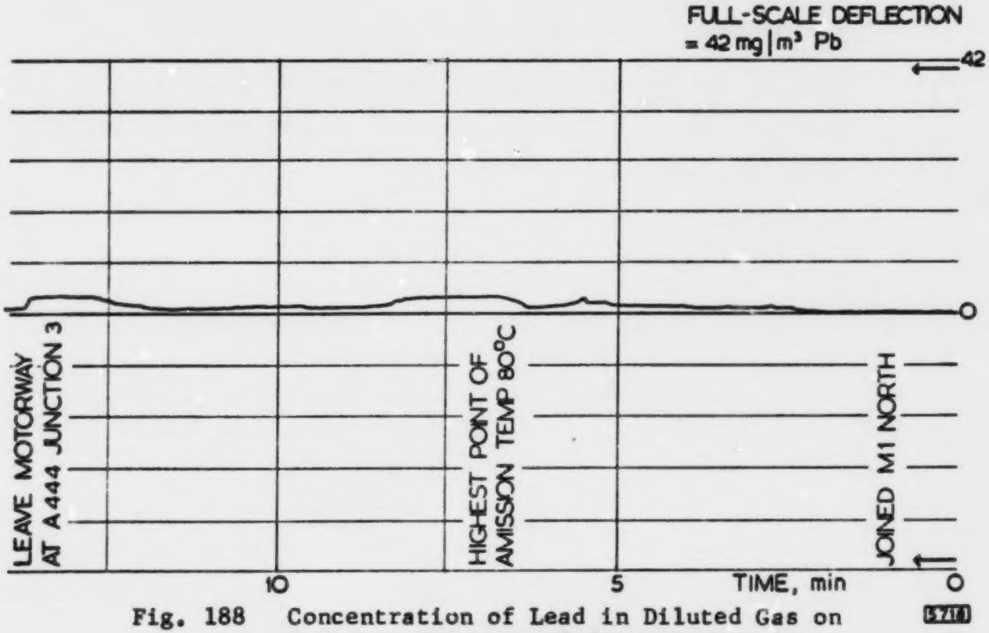

Fig. 188 Concentration of Lead in Diluted Gas on Motorway Section — 3.0 Liter Vehicle

APPENDIXES

APPENDIX A

List of Attendees and Representatives

APPENDIX A

LIST OF ATTENDEES AND REPRESENTATIVES

Official Delegates

NATO HEADQUARTERS

Prof. Nimet Ozdas
Assistant Secretary General for Scientific and Environmental Affairs

FRANCE

Mr. Bernard Belier
Citroen (New York)

Mr. Pierre Bouthors
Renault

Mr. Claude Lamure
(Head of Delegation)
Transport Research Institute

FEDERAL REPUBLIC OF GERMANY

Mr. Frielingsdorf
Daimler Benz AG

Dipl. Ing. D. Gwinner
Daimler Benz AG

R.D. Dr. Dieter Hartmann
(Head of Delegation)
Ministry of Interior

Prof. Dr. H. Heitland
Volkswagen Werk AG

Dr. W. H. Hucho
Volkswagen Werk AG

Dr. Kuhlmann
Maschinenfabrik Augsburg-Nuernberg AG

Dipl. Ing. L. Sienonik
Kloechner-Humboldt-Deutz AG

Dr. P. Walzer
Volkswagen Werk AG

R. D. Zemlin
Ministry of Research & Technology

ITALY

Eng. Vincenzo Opportuno
(Head of Delegation)
Ministry of Transport

Mr. G. Savonuzzi
Fiat Motor Company

THE NETHERLANDS

Mr. J. G. Kuiperbak
(Head of Delegation)
Highway Traffic Service

Engr. A.P.J. Michels
Philips

Mr. L.C. Van Beckhoven
Ministry of Health

SWEDEN

Mr. Rolf Andreasson
Scientific Attache
Swedish Embassy

Mr. Jan Ellbjar
Volvo

Prof. S. O. Kronogard
Turbokonsult

Mr. Olle Ljungstrom
(Head of Delegation)
Swedish Board on Technical Development

Mr. Lars Ortegren
United Stirling

Mr. Ove Platell
Saab-Scania

Mr. Bengt Schmidt
Saab-Scania

Dr. John Stahlblad
Turbokonsult

UNITED KINGDOM

Mr. James Barnes
British Embassy - Washington, D.C.

Mr. George Donald
(Head of Delegation)
Department of Environment

UNITED KINGDOM (cont.)

Mr. R. Lindsay
Shell International Petroleum Co.

Mr. S. Wallin
Department of Trade & Industry

Dr. D. L. Wilson
Department of Trade & Industry

UNITED STATES OF AMERICA

Mr. John J. Brogan
Director, Alternative Automotive Power Systems Division
Environmental Protection Agency

Mr. Fitzhugh Green
Assoc. Administrator for International Activities
Environment Protection Agency

Mr. Frank Hodsoll
Council on Environmental Quality, NATO/CCMS

Dr. Kay H. Jones
Director, NATO/CCMS Air Pollution Pilot Study
Environmental Protection Agency

Dr. John W. Ludwig
Symposium Rapporteur

Mr. Eric O. Stork
Deputy Asst. Administrator
Office of Mobile Source Air Pollution Control

Mr. George M. Thur
Symposium Organizer

EMBASSIES

JAPAN - Mr. T. Ichikawa

THE NETHERLANDS - Mr. C.H. Van Vierssen

SWEDEN - Mr. Rolf Andreasson

COUNCIL ON ENVIRONMENTAL QUALITY
Advisory Committee on Alternative Automotive Power Systems

Dr. Joseph Coates
Program Mgr., Exploratory Research & Problem Assessment
National Science Foundation

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U. S. Postal Service

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Director, Research-Product & Planning
Chrysler Corporation

Mr. David F. Moyer
Director, Systems Research Lab
Ford Motor Company

Mr. Ernest Starkman
Vice Pres., Environmental Activities Staff
General Motors Technical Center

Dr. Richard L. Strombotne
Asst. for Physical Sciences
Department of Transportation

Mr. Robert Ullrich
General Services Administration

Press

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Ann Arbor News

Ms. Janice Crossland
Environment

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Chilton Business Publications

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Mr. Fred Moncrieff
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Mr. Roger Rowand
Automotive News

Mr. Wally Scott
TV Channel 2
Detroit, Michigan

Mr. Vince Wade
TV Channel 7
Detroit, Michigan

Mr. Douglas Williams
Detroit Free Press

Mr. Dick Witkin
Editor, Transportation
New York Times

Industrial Organizations (World-Wide)

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AEROSPACE CORP.	Lapedes, Don Roessler, Wolfgang
AIRCO CRYOGENICS	Beveridge, John H.
AIRESEARCH CORP.	Anderson, C.J. Dawson, David Lewis, Leon McKinley, Larry
AMERICAN OIL CO.	Huber, Paul
AMERICAN MOTORS	Burke, Carl E. Green, Raymond J. Martin, William
ARA - SAN ANTONIO	Bunch, Howard M.
ARTHUR D. LITTLE INC.	Hurter, Donald Matthews, Harry
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AVCO CORP.	Bentele, Dr. Max
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BEECH AIRCRAFT	Hibl, J. J.
BENDIX CORP.	Datwyler, Walter
BORG WARNER CORP.	Hallberg, Irving
BROBECK ASSOCIATES	Euckel, Warren
BROOKHAVEN NATIONAL LAB	Hoffman, Ken Waide, Charles
CALIFORNIA RESEARCH	Renner, Roy Wenstrom, Michael

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	Zadoks, Abraham
CELANESE CHEMICAL CO.	Baker, Norman
CHAMPION SPARK PLUG	Lentz, L. R.
CHANDLER EVANS	Jahrstorfer, George
	Riordan, Mike
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	Angell, Peter
	Ball, G. A.
	Benvenuti, R.
	Carry, Bill
	Collister, Howard
	Engel, J. H. Jr.
	Eshelman, Robert W.
	Fleming, Brian
	Franceschina, J. P.
	Golec, Thomas
	Huebner, George J. Jr.
	LeFevre, H. P.
	Lunan, James
	Mann, L. B.
	Marlotte, J. A.
	Martin, F.
	McNulty, Wm. L.
	Miklos, A. A.
	Noftz, M. E.
	Roy, A.
	Schleicher, Bob
	Schmidt, Fred
	Stecher, George
	Stempien, Bill
	Valene, Ross
	Wagner, Charles
	Whitfield, J. H.
	Wilson, P. J.
CITROEN	Belier, Bernard
COLT INDUSTRIES	Wen, M. K.
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	Gay, Errol J.
	Harmon, Robert A.
	Roensch, Max M.
	Underwood, Art

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DAIMLER BENZ AG	Frielingsdorf, Mr. Gwinner, Dipl. Ing. D.
DAUVERGNE BROTHERS INC.	Moore, C. W.
D-CYCLE POWER SYSTEMS	Burke, Jerry Jr.
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ESSO RESEARCH	Appeldoorn, John Herbst, W. H. Kant, F. May, W. G.
ETHYL CORP.	Adams, W. E. Lenane, Denis
EXCELLO CORP.	Weldy, R. K.
FEDERAL MOGUL	Probst, Robert L.
FIAT MOTOR CO.	Savonuzzi, G.

FORD MOTOR CO.	Chapman, W. I.
	Davis, D. A.
	Galiardo, J. C.
	Howes, B.
	Jones, J. H.
	Kitzner, E. W.
	Kostun, John
	Macauley, Wm.
	McLean, A. F.
	Moan, R. D.
	Paluszny, A.
	Peters, Norman
	Phillips, C. W.
	Smith, W. R.
	Stockton, T. R.
	Taylor, Gordon
	Wade, W.
	Walch, H.
	Wales, W. W.
FOSECO	Rice, Ron
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GARRETT CORP.	Bartlett, Parker M.
	Dawson, David
	Flinn, Donald E.
	Mason, John
	McInerney, Chuck
	Perry, Duane C.
	Stimac, A. E.
GENERAL ELECTRIC CO.	Becroft, W.
	Brooks, Robert
	Eckard, S. E.
	Stanko, David
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	Nelson, S. E.
	Sullivan, Robert
	Verdouw, Albert
GENERAL MOTORS TECHNICAL CENTER	Agnew, Dr. Wm.
	Amann, Charles
	Bell, A. H.
	Collman, John
	Cornelius, Dr. Walter
	Cronk, E.
	Fleming, J. D.
	Frederiksen, Hans
	Hammond, D. C.

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	Heffner, Earl
	Heullmantel, L. W.
	Heitbrink, Earl
	Hitzelberger, A. L.
	Jacobsen, E. G.
	Johnson, Paul
	Krieger, R.
	Malik, M. J.
	Martyniuk, E. T.
	Matthews, Charles
	McDonald, J. L.
	Naylor, Mike
	Nicholson, R. C.
	Niepoth, George
	Nordenson, G. C.
	Percival, Worth
	Pringle, Pat
	Sheridan, David
	Siegla, D. C.
	Skellenger, G.
	Stebar, R. F.
	Stettler, R.
	Talder, R. W.
	Vickers, Paul
	Wyczalek, Floyd
GENERAL RESEARCH CORP.	Hamilton, Wm.
HALOCARBON PRODUCTS CORP.	Ferstandig, L. L.
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HERCULES DIVISION - WHITE MOTOR CO.	Hatonada, Toru
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	Nagler, L. H.
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	Paul, R. H.
	Schwartz, F. C.
HOLLY CARBURETOR	Brantman, Leon
HONDA R & D	Hatanaka, Toru
HOWMET CORP.	Schuiteman, Ray
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	Caudler, B. J.

INSTITUTE OF GAS TECHNOLOGY	Gillis, Jay Pangborn, Dr. John
INTERNATIONAL NICKEL CO.	Billin, R. M. Tuffnell, Glenn W.
ISUZU MOTORS LIMITED	Tsukagawa, Satoru
KELSEY-HAYES	Good, William Karwan, Bill
ROBERT A. KEYES ASSOCIATES	Schweppe, Howard
KLOECHNER-HUMBOLDT-DEUTZ AG	Sienonik, Dipl. Ing. L.
KOMATSU MANUFACTURING CO.	Miyamaru, Toshimichi
KRUSE ENGINEERING	Kruse, Douglas
LEAR MOTORS CORP.	Camomile, David Delligatti, J. Louis Hood, Delos Kahn, Ronald Lear, William Morris, Del Swanfelt, Robert
LUBRIZOL	Sieloff, Frank
3M COMPANY	Johnson, W. C. Schmitt, Joseph
MASCHINENFABRIK AUGSBURG-NUERNBERG AG	Kuhlmann, Dr.
MCCORD CORP.	Kargilis, Alexander
MECHANICAL TECHNOLOGY, INC.	Decker, Otto Sternlicht, Dr. Beno
MERCEDES-BENZ	Arndt, Fred Scherenberg, Volker
MITRE CORP.	Fraize, W. E. Jacobsen, W. E.
MITSUBISHI MOTOR CORP.	Kwshiyama, T. Nakahara, Takabumi Satoh, H. Tokizane, T. Tonomura, Yoshihito

MOBIL R & D CORP. - MOBIL OIL CO.	Crosthwait, Richard
MONSANTO CORP.	Miller, Dr. David Winslow, Frank J.
NIDEA	Dean, John
NISSAN MOTOR CO., LTD.	Ariga, Hajime Maeda, R. Nakamura, Y. Saito, T.
JOSEPH LUCAS NORTH AMERICAN, INC.	Burgess, Anthony J. Johnson, Ian
NORTH AMERICAN PHILIPS CO.	Loeffler, Lawrence E.
NORTH AMERICAN ROCKWELL-ROCKETDYNE	Bremer, George F.
NORTHERN RESEARCH CORP.	Demetri, Elia
ONAN, DIVISION OF WORTHINGTON CORP.	Drury, E. A. Lehmann, W. J.
ORGANIZATIONAL CONTROL SYSTEMS	Dorrance, W. H.
OWENS ILLINOIS	Kormanyos, Ken R. Oster, E. A. Pei, Y. K. Ramelmeier, Rolf W.
NOEL PENNY TURBINES	Candy, Peter Noble, Dr. David
PERKINS ENGINE CO.	Bertodo, R. Hartwell, N.
PEUGEOT	Lucki, Richard Bureau, Mr. Noel
N.V. PHILIPS RESEARCH LABORATORIES	Michels, A.P.J.
PHILIPS PETROLEUM CO.	Schirmer, R. W.
RAY POTTER & ASSOCIATES	Potter, Raymond I.
PRATT WHITNEY AIRCRAFT	Billman, Low Green, Ken
RENAULT	Bouthors, Pierre

RICARDO CONSULTING ENGINEERS	Downs, Diarmuid
ROHR CORP.	Nicita, John
ROLLS ROYCE MOTOR LTD.	Astbury, J. B. Preece, D. G. Weston, C. A. Williams, T.
ROTARY VAPOR ENGINE CO.	Batton, Bill
RRC INTERNATIONAL LAB	McKenna, Charles Jr.
SAAB-SCANIA	Schmidt, Bengt Platell, Ove
SCIENTIFIC ENERGY SYSTEMS CORP.	Chittick, Charles Demler, Roger Gerstmann, Joseph Hoaglund, Lawrence Morse, Dr. Richard Synuita, Walter Vernon, Jack
SHELL OIL CO.	Burstain, I. G. Doyle, Marshall Glockner, Peter
SOLAR, DIV. OF INTERNATIONAL HARVESTER	Compton, W. A. White, David
SOUTHWEST RESEARCH INSTITUTE	Colburn, John W. Jr.
SUN OIL CO.	Toulmin, H. A.
SUN COAST RESEARCH	Loomis, W. Warren
SUNDSTRAND AVIATION	Niggemann, Richard
TELEDYNE CONTINENTAL MOTORS	Altman, Peter Berenyi, S. G. Brevick, Edward G. Gasaway, C. Mott, D. Pearsall, Thomas J. Requeiro, Jose F.
TEXACO, INC.	Johnson, Everett M.
THERMO ELECTRON CORP.	Armstrong, Jack David, Terry

THERMO ELECTRON CORP. (Cont.)	Doyle, Ed Hatsopoulos, Dr. George Patel, Parimal S. Sakhaja, Ravi
TOYO KOGYO LTD.	Yamate, Noriaki
TOYOTA MOTOR CO., LTD.	Hakajima, K. Kinoshita, T. Nakamura, Kenya Takagi, H. Tomita, K.
TRW EQUIPMENT	Saslaw, Robert L
TURBOKONSULT	Kronogard, Prof. S. O.
UNION CARBIDE	Gehres, Dr. E.
UNITED AIRCRAFT OF CANADA	Eatock, Claire
UNITED STIRLING	Ortegren, Lars
VOLKSWAGEN WERK AG	Heitland, Prof. Dr. H. Hucho, Dr. W. H. Walzer, Dr. P.
VOLVO	Ellbjar, Jan
WHITE ENGINEERING	Taggart, Charles I.
WILLIAMS RESEARCH	Fant, Rick Huben, C. Hulbert, John Williams, Sam
YAMAHA INTERNATIONAL CORP.	Greer, J. B. Ito, Kenneth Lake, Leo Seino, T.

U. S. Government Agencies and Organizations

ARMY FUELS & LUBRICANTS RESEARCH LAB	Moses, Clifford
ARMY MOBILITY EQUIPMENT R/D CENTER	Daniels, J. Harrison Horton, James Summerson, Wm.

ARMY TANK AUTOMOTIVE COMMAND	Bryzik, Walter
	Checklich, George
	Farkas, Alexander J.
	Huber, Herbert
	Raggio, David G.
	Santo, H.
	Scully, Andres
BROOKHAVEN NATIONAL LAB	Hoffman, Ken
	Waide, Charles
BUREAU OF MINES	Chamberlain, Thomas
	Hurn, Richard
DEPARTMENT OF COMMERCE	Larson, Clayton, J.
DEPARTMENT OF TRANSPORTATION	Compton, Roger
	Dilorenzo, Francis
	Gould, Herbert H.
	Hergenrother, Dr. Karl
	Husted, Robert
	Kaplow, Michael D.
ENVIRONMENTAL PROTECTION AGENCY - Ann Arbor, Michigan	Bascanana, Jose
	Barber, Ken
	Beyma, Ed
	Cain, Bill
	Chenney, Mitch
	Clopton, Lewis
	Conroy, Kerrins
	Garvey, James
	Gompf, H.
	Hopkins, Howe
	Hutchins, Peter
	Kaykaty, Gabriel
	Kenney, Dyer
	Kramer, Saunders B.
	Lawrence, Dick
	Luchter, Steve
	McFadden, Jack
	Mirsky, Wm.
	Murrell, Dill
	Naser, Howard
	Pax, Charles
	Perkins, Dave
	Plungis, Donald
	Schulz, Robert
	Sebestyen, Tom
	Stahman, Ralph
	Sutton, Pat
	Szczepaniak, Ed

ENVIRONMENTAL PROTECTION AGENCY - Washington, D. C.	Hardesty, Jack Johnson, James C. Myers, Nancy Pirkey, Diane Romanovsky, Jerry C. Schoen, Dr. Louis
GENERAL SERVICE ADMINISTRATION (See Advisory Committee on AAPS)	
NASA HEADQUARTERS - Washington, D. C.	LaRock, Col. Ralph
NASA-LEWIS RESEARCH CENTER	Butze, Fritz Heller, Jack Joyce, Joseph Kempke, Pete Mackin, James Meng, P. R. Ream, Lloyd Ribble, Guy Rohlik, H. Stone, Phil Wintucky, Wm.
NATIONAL SCIENCE FOUNDATION	Topper, Dr. Leonard
NAVAL ENGINEERING CENTER	Womer, W. Zacharkiw, P.
POSTAL SERVICE (See Advisory Committee on AAPS)	

Educational Institutions

CARNEGIE MELLON UNIVERSITY	Macken, Dr. Nelson Paul, Dr. Frank
LAWRENCE INSTITUTE	Davis, Stephen R.
UNIVERSITY OF MICHIGAN	Bolt, Prof. Jay Clark, John Cole, Prof. David Deininger, Prof. R. A. Hansen, Kai Kubota, Shoji Nichols, Prof. J. Smith, Gene E. Yang, Dr. Wen

MICHIGAN STATE UNIVERSITY	St. Clair, Charles Jr.
PASADENA CITY COLLEGE	Edgar, Lawrence
UNIVERSITY OF RHODE ISLAND	Brown, Prof. G. A.
WAYNE STATE UNIVERSITY	Henein, N. A. Singh, Dr. T.

APPENDIX B

Background and Evolution of CCMS/LPPSD Leading to the Signing of the Annex Agreement on the Memorandum of Understanding by the Government Representatives.

Background: At a special ceremonial session of the North Atlantic Council in April 1969, commemorating the twentieth anniversary of the signing of the North Atlantic Treaty, President Nixon urged that NATO add a new dimension to her activities. In addition to the military and political aspects, he recommended that the Alliance become involved in social problems related to the improvement of the quality of life for her people in the last third of the twentieth century. Article II of the North Atlantic Treaty, adopted in 1949, had provided for such activities when the parties agreed to "... contribute toward the further development of peaceful and friendly international relations by...promoting conditions of stability and well being..."

Establishment of CCMS: At its November 1969 meeting, the North Atlantic Council formally established the "Committee on the Challenges of Modern Society" (CCMS) to deal not only with problems of pollution-- air and water, solid waste, noise, etc.,-- but also with more general social problems that stem from technological development. The aims of the Committee are to develop meaningful programs that do not explicitly duplicate other international programs underway but compliment them. The goal is to show leadership, first in solution of existing problems and second in development of long-range goals for environmental protection in the NATO sphere of influence and in other countries as well.

The Air Pollution Pilot Study: At the first plenary session of the CCMS, officials of the Office of Air and Water Programs, as members of the U. S. delegation, presented a proposal for an air pollution pilot project. The Governments of the Federal Republic of Germany and Turkey responded favorably and became co-pilots with the U. S. in this endeavor. Other NATO members are also participating in observer capacities in activities of the study.

The Working Group in charge of the Study met for the first time in Ankara, Turkey in March 1970. The Working Group adopted an action program designed to demonstrate the utilization of existing knowledge for the development of rational, long-range air pollution control programs. The Pilot Study, with work divided into two "phases," embodies three basic elements of the system required to develop a rational long-range air pollution abatement program: first, the assessment of present and future air quality; second, the development of air quality criteria; and third, the assessment of available control technology. To assess these three basic elements of the system, four major tasks have been outlined:

(1) Task I. Assess ambient levels and sources of pollutants in one major urban region in each country for both present conditions and projected growth for the next twenty years.

(2) Task II. Select appropriate mathematical diffusion modeling techniques to relate source emissions to ambient air quality for application to Task I.

(3) Task III. Promulgate air quality criteria documents.

(4) Task IV. Promulgate control technology documents.

In addition to a "guidelines" document outlining basic methodology to be used in an assessment study, results of studies in Ankara, Turkey, St. Louis, Missouri, and Oslo, Norway have been published to date and the Frankfurt, Germany, study report will be published within a few months. Increased participation in the pilot study since its inception has led to studies being planned or underway for Milan and Turin, Italy, and Rotterdam, The Netherlands. Air quality criteria documents have been published for particulates, sulfur oxides, carbon monoxide, and nitrogen oxides. Control techniques documents for emissions of sulfur oxides, particulates, carbon monoxide, hydrocarbons, and nitrogen oxides from stationary sources are currently being developed.

The LPPSD Program: One of the goals of the ongoing CCMS air pollution project is to demonstrate assessment techniques for determining the impact of automobile pollution as well as evaluating the efficacy of various control strategies. Such a program would be of interim benefit in assisting European manufacturers in meeting emission standards established by various countries.

The Memorandum of Understanding on LPPSD: In light of this need for development of low pollution vehicles among the NATO allies the United States, in November 1970, as part of the Air Pollution Pilot Study, introduced the Low Pollution Power Systems Development (LPPSD) Program. As a result of this initiative, a conference was called to discuss LPPSD the following February in Eindhoven, The Netherlands. At this conference a Memorandum of Understanding was circulated by the United States among the assembled nations. The proposed multi-lateral agreement would become the framework for cooperation in LPPSD among auto-producing NATO countries in the future.

Signing of the Agreement: On November 14, 1972, at the CCMS Plenary meeting at NATO Headquarters in Brussels, six nations signed the Memorandum. These nations were: The United Kingdom, France, Italy, Germany, The Netherlands, and the United States.

Provisions of the Memorandum call for:

- Direct information exchange.
- Technical symposia.
- Collaborative projects.

U. S. Contribution to Exchange Program: The U. S. input to the LPPSD information exchange will come from the
(AAPSP) which provides for Federally sponsored research and development to produce an unconventionally powered, virtually pollution-free automobile. The current effort is being focused on three engine systems: gas turbine, Rankine-cycle system, and the stratified charge engine. These three systems have been selected because they offer the highest potential of being developed at the earliest time into practical systems which are virtually pollution free and which can be competitive in performance with the conventional internal combustion engine. Development of hybrid and battery systems has been deferred at the present time.

APPENDIX C

"Review of Conditions, Circumstances, and Evolution of Present Stringent Automobile Emission Standards"

Luncheon Remarks by:

Eric O. Stork
Deputy Assistant Administrator for
Mobile Source Air Pollution Control
Office of Air and Water Programs, EPA
October 17, 1973

For the past two and a half days, we have been hearing about what the future may hold for us in terms of new engine systems for automotive transportation. We will hear more during the rest of this week. But I think that it may also be useful to take a brief backward look, and to review the conditions and circumstances that have brought the United States to the stringent automobile emission standards that we have today, and that other countries are also adopting in various degrees. To take such a look may help place into context our continuing deliberations about the low-pollution hardware that hopefully will result from our joint efforts.

Concern about air pollution is a post-World War II phenomenon. As this concern grew, it was discovered that in our congested urban areas the automobile was a major -- if not the major -- cause of air pollution. Clearly, if the air was to be cleaned up something had to be done to control the emissions from automobiles.

Action to do something about air pollution that is caused by automobiles began in California. Beginning with the 1963 model year, California required all new automobiles to be equipped with closed crankcases. A significant portion of the total unburned hydrocarbon that was getting into the ambient air came from crankcase vents; those of you here old enough to recall will know that prior to these changes, automobiles had a breather pipe running down to the bottom of the engine that allowed crankcase vapors to be sucked out of the engine as the car moved along; however, the new positive crankcase ventilation (PCV) systems recirculated these crankcase vapors into the fuel/air intake system, to be burned in the engine. The auto industry voluntarily installed PCV on all cars sold in the United States shortly after California set this requirement.

Effective with the 1966 model year, California required new automobiles to control exhaust pipe emissions. These controls at that time applied only to unburned hydrocarbons and to carbon monoxide, and provided that prior to being allowed to sell cars in the state of California, a manufacturer had to demonstrate that his vehicles were within the allowable limits for emissions of these two pollutants. The Federal government followed suit two years later, by establishing essentially similar emission control standards on a nationwide basis. These standards were made more stringent effective with the 1970 model year automobiles, and for the 1972 model year.

As regards oxides of nitrogen, California added control of this pollutant to its standards effective with the 1971 model year. The Federal government followed suit by requiring control for oxides of nitrogen nationally for the 1973 model year. That, pretty well, is where the matter stood by the summer and fall of 1970, when the Congress was considering extension of the Air Quality Act of 1967.

Clean Air Amendments of 1970: Now let's look at the action that the Congress took in 1970. As you all know, the Clean Air Amendments of 1970 provide for extremely stringent emission limitations for automobiles for hydrocarbons and carbon monoxide in the 1975 model year, and for nitrogen oxides in the 1976 model year. To understand what the Congress did, and why it did it, we have to look at the rationale for taking action in emission control that proceeded this particular piece of legislation.

All of the standards that I described in my foregoing remarks, up through the 1973 oxides of nitrogen standard, have reflected judgments of degrees of emission control that were reasonably achieveable in terms of known technology, within a given timetable for implementation. That is not to say that everything that has been required by the Federal government up till now in the field of automobile emission control has been easy for the industry to do. In some cases, it has been so far from easy that industry has found it necessary to drop certain models because they could not meet the emission control standards. However, on the whole there never was any real question about whether it was possible for industry to comply with the emission standards up through the 1973 NOx standard; the only question that might arise is how much it would cost to meet those standards in terms of increased price of vehicles; and how much it would cost to meet those standards in terms of reduced vehicle performance and reduced vehicle fuel mileage.

While such a policy for setting emission standards was being pursued, there was also a search to define the degree of emission control that would ultimately need to be achieved so that air quality standards in our major urban centers could be met. In June of 1970, a now famous paper was given by Dr. Delbert Barth, Director of the Bureau of Criteria and Standards of the National Air Pollution Control Administration. Dr. Barth presented this paper at the 1970 Annual Meeting of the Air Pollution Control Association in St. Louis.

In that paper, Dr. Barth set forth an approach for determining the emission levels from vehicles that might ultimately be required to meet air quality standards. By making a number of assumptions, some of which I will mention in a moment, Dr. Barth developed 1980 automobile emission goals for carbon monoxide, hydrocarbons, and oxides of nitrogen, and expressed these goals in terms of a percentage reduction of these pollutants from baseline values emitted by uncontrolled automobiles. In that paper, Dr. Barth suggested that carbon monoxide would need to be reduced 92.5% from the levels emitted by uncontrolled vehicles; oxides of nitrogen, 93.6%, and unburned hydrocarbons, 99.0%.

Now a few words about the assumptions made by Dr. Barth in his analysis. Basically, he categorized this analysis as a simple proportional rollback approach, modified to the extent appropriate by a projection of growth factors in pollutant sources, and by pollutant background levels. Dr. Barth assumed that if the ambient level of a given air pollutant is three times the desired level, then to achieve the desired level it is necessary to reduce emissions of that pollutant by two thirds. Dr. Barth fully recognized that the relationship between ambient levels of pollutants, and emissions of that pollutant, may or may not be linear, but in the absence of specific data for such a relationship he assumed a linear relationship. Furthermore, for purposes of his analysis, Dr. Barth assumed that all sources of any given pollutant would be reduced to the same degree; his analysis makes no pretense to dealing with the question of whether or not it is in fact possible to reduce all sources to the same degree, or conversely whether it is necessary to reduce some sources more so as to make up for the reduction that cannot be achieved from other sources.

Dr. Barth considered his paper to be a step in the process of developing a validated methodology for determining the levels of emission control that are needed to achieve air quality goals. In his paper, he emphasized the limitations and uncertainties inherent in his analysis. However, this tool for analysis represented a major step forward; and as such it came to the attention of Senate Committee which at that time was considering the extension of the Air Quality Act of 1967. Barth's analysis had dealt with 1980 emission goals, but the Senate Committee concluded that air pollution was so serious a problem that the timetable for achieving air quality standards had to be shortened. Using among other inputs the Barth analysis, the Senate Committee provided that 1975 model year vehicles may emit no more than 10% of the HC and CO that was allowed to be emitted by 1970 model year vehicles; since at that time there were no emission standards in effect for oxides of nitrogen, the Committee provided that 1976 vehicles would be limited to 10% of the emission of oxides of nitrogen that were actually emitted by the average 1971 model year vehicle that was not specifically controlled for that pollutant.

The Clean Air Amendments of 1970 as finally passed by Congress incorporated those limitations on emissions, and also provided that the Administrator of EPA was to promulgate within 180 days of enactment of this law the final standards and test procedures on the basis of which 1975 automobiles would be judged. Shortly after the passage of that new law, we got to work on this matter, and did manage to get the standards and test procedures promulgated in the time provided.

Now, the important thing to keep in mind about these 1975/76 standards is that they were established without any demonstration of the availability of technology that may be needed to achieve such standards. They were established by the Congress in terms of the best information available to the Congress as regards the level of emission control that is necessary to adequately protect air quality in our urban areas. This way of setting emission standards, therefore, is a major departure from the way in which such standards were set in the past; up through the 1973 standards, while the concern about air quality was of course the reason for imposing emission controls in the first place, the degree of emission control that was imposed was limited to what was known to be possible of achievement.

Current Situation: Well, where are we now? The standards became law, but the story didn't end there. Because it was recognized that it might not be possible for industry to meet the standards on the time schedule set forth in the Clean Air Act of 1970, the Congress gave the Administrator authority to suspend the applicability of these standards for a period not exceeding one year. The Congress gave the Administrator some rather specific criteria on the basis of which to consider industry requests for extension of the standards: The Administrator had to find that such a suspension is essential to the public interest or to the public health and welfare of the United States; that all good faith efforts have been made to meet the standards by those who apply for a suspension; that the applicant has established that effective control technology, processes, operating methods, or other alternatives are not available or have not been available for a sufficient period of time to achieve compliance prior to the effective date of such standards; and that a study and investigation by the National Academy of Science also indicate that technology and so forth is not available. These are pretty tough ground rules.

In the Spring of 1972, several major automakers exercised their right to ask for a one-year suspension of the 1975 HC and CO standards. After public hearings that lasted thirteen days, and after review of thousands of pages of technical material, former Administrator Ruckelshaus denied these requests, on May 12, 1972. He denied the suspension requests at that time because, in his judgment, the applicants had not established that control technology adequate to meet the Clean Air Act requirements for 1975 cars is not available.

At the press conference announcing the denial of the suspension requests, the Administrator was asked to comment on the assertion by some automobile companies that his failure to suspend the application of the 1975 standards would mean that no automobiles would be produced in 1975. Mr. Ruckelshaus responded to this question by saying that he considered that view to be completely unrealistic. He pointed out that the automobile manufacturers had several options available. One option, he said, was to get to work and meet the standards. Another option, he pointed out, was to challenge his decision in court. Thirdly, he pointed out, the automobile makers were free under the law to come back and apply again for a suspension of the standards. He emphasized, however, that he anticipated that a good deal of additional development and testing would be undertaken by the automobile companies before they might come back again with a request for a suspension; an immediate request of this type, he pointed out, would raise serious doubt about the "good faith" of the automobile companies toward meeting the 1975 standards.

The companies promptly went to the courts to challenge Mr. Ruckelshaus' action. Early this year, the U.S. Court of Appeals for the District of Columbia rendered its decision. The Court remanded the case to the Administrator for further consideration, and in doing so provided significant new criteria on the basis of which the decision on a request for suspension had to be made. Key among these, the Court expanded the concept of technological feasibility of meeting the standards to include consideration of the capability of the industry in meeting the basic demand for new cars; in other words, unless the Administrator could find that most of the people who want to buy new cars in 1975 can do so, technological feasibility to meet the standards does not exist.

And thus was launched the second round of Suspension Hearings. Within 60 days of the Court of Appeals action the EPA Administrator had to make a new decision on the remanded petitions. Again we had almost three weeks of hearings, sometimes lasting well into the evening. Again thousands of pages of technical data were submitted and reviewed. It became clear in those hearings that the automakers had made a lot of progress during the intervening year -- many more cars had been tested to higher mileage, and quite a few successfully. Much work had been done to improve catalytic converters. In addition, the Toyo Kogyo company, which had said in the 1972 hearings that they thought they could meet the standards with their rotary engine without catalysts, had by the end of 1972 actually demonstrated this; and the Honda company had done the same with their carbureted version of a stratified charge reciprocating engine. Nevertheless, most automakers still argued with vigor that the only way in which they could meet the standards was with the use of catalysts, and that they could not meet the standards in 1975 and still meet basic demand, as the Court had said was the real measure of technological feasibility. Furthermore, the companies placed great emphasis in the hearings on the need to phase in so new a device as a catalyst. We heard a great deal about the catastrophic results that could come from a requirement to use catalysts on all cars. Visions of the entire auto industry being shut down because of unanticipated problems with catalysts were danced before our eyes. Two companies -- Ford and GM -- proposed that two sets of standards be set: One more stringent set, requiring the use of catalysts, for California; and one less stringent and not requiring catalysts for the rest of the nation. This, they argued, would permit experience with catalysts to be accrued on a less than national scale, and would also allow them to put into a limited area of the country whatever resources might be needed to make sure that any catalyst failures were promptly corrected on customer cars.

When Administrator Ruckelshaus announced his second suspension decision, on April 11 of this year, he concluded that in weighing the potential societal disruption involved in attempting to apply catalytic technology across all car lines in one year, against the minimal air quality impact of a one-year suspension with stringent interim standards, the better part of wisdom was to phase in the use of catalysts. So the automakers got their suggestion of a two-standards system, although both the standards for California -- which in our judgment would require the use of catalysts -- and the standards for all other cars, which would not require catalysts, were significantly more stringent than the automakers had suggested.

After their initial negative reactions to the decision, the auto companies apparently decided that they could meet the interim standards; I suspect that they figured that they had more to lose from extending the period of uncertainty about what sort of cars would be produced in 1975 than they might gain from another appeal. In any case, they soon announced that they would comply.

I think that it is interesting to note at this point that only a couple of months later GM announced that it would install catalysts on most of their 1975 cars -- and not just on the California ones. Ford too has since said that it expects to have catalysts on some non-California cars. In June of this year GM announced its plan to use a "lifetime" catalyst that would last for 50,000 miles, and went on to promise that those catalyst-equipped cars would perform better, and have better fuel economy, than comparable 1973 cars. We may be forgiven if we feel that these developments strongly justify the tough positions taken by the EPA Administrator on both suspension decisions -- we believe that these decisions have pushed the companies just about as far as they could be pushed, by the 1975 model year, in the direction of building clean cars.

But we were not yet done with Suspension Decisions. There was still the 1976 NOx standard. Not only was it generally recognized that meeting a very stringent NOx standard would be much more difficult than meeting the HC and CO standards, and that stringent NOx control might increase fuel consumption significantly; in addition, EPA had discovered and reported to the Congress that the data on which the Congress based the statutory NOx standard was faulty, and that there was now doubt about the need for so stringent an NOx standard. So when the companies applied for a suspension of the NOx standard around the beginning of June of this year, another complete set of hearings had to be held. This time, however, it was a different story. Unlike the hearings on suspension of the HC and CO standards, at the NOx hearings no one -- neither automakers nor catalyst producers nor component suppliers -- no one asserted that the suspension should be denied on the grounds of technical feasibility.

While much information was developed which suggests that with future development effective and economical (in terms of fuel used) catalytic NOx control may become feasible, no one said that this could be done so as to meet basic demand for new cars in the 1976 model year. Our technical staff came to the same conclusion. Thus on July 30, 1973, the then Acting Administrator, Robert Fri, granted a one-year suspension of the 1976 NOx Standard, and imposed an interim NOx standard that can be met without the use of an NOx catalyst.

And that's where we are today. Under the law, the statutory standards must now be met in 1976 for HC and CO, and in 1977 for NOx. In the meantime, stringent interim standards will apply to 1975 and 1976 cars. The EPA continues to believe that the statutory NOx standard is not needed to protect health and welfare, and we expect the Congress to address this matter later this year. The auto companies, of course, have made it clear that they will try to get the Congress to change not only the NOx standard but also the HC and CO standards. The EPA has continued to advise the Congress that the HC and CO standards are both necessary and achievable. The next round of decisions must come from the Congress.

Let me close this review on a personal note. I am convinced that had the Congress not done as they did in 1970, then 1975 and subsequent model year cars would not have even gotten close to being so clean as they are now going to be. By putting on the auto industry the very great burden of having to try to prove a negative -- i.e. that they could not meet a standard -- that industry was spurred on to far greater efforts than we could otherwise have motivated them to undertake. Those efforts resulted in enormous progress in the technology of emission control -- progress that will accrue to the benefit of our nation's city dwellers in the years to come.

In our complex society, it may well be this sort of unequivocal action that is the only thing that can get completely serious attention in corporate boardrooms. Maybe it does take such action to persuade top management in so huge an industry that their engineer's creative energies are better utilized on socially worthwhile efforts than on frills like tail fins, vinyl roofs, and disappearing windshield wipers. Because of the Clean Air Act, we can have confidence that the cars of the future will be a far lesser factor in the fouling of the air that all of us must breath every day of our lives.

APPENDIX D

Hardware Exhibits

The following is a list of the exhibits which were displayed and operated during the Symposium along with a few selected photographs.

GAS TURBINE:

- 1 Gas Turbine Vehicle 1973 Model (Chrysler) (Driveable) (See Figs. E-1 and 2)
- 1 Gas Turbine Engine Mockup (Chrysler)
- 1 Gas Turbine Rotating Hardware Display
- NASA Low Cost Engine Program Parts
- NASA High Performance Aero. Components
- Low Emission Combustor displays
- Low Cost Turbine Wheels
- Ceramic Regenerators and Recuperators
- 1 EPA/Williams Gas Turbine Car (Driveable) (See Fig. E-3)
- Williams Gas Turbine Mockup

RANKINE SYSTEM:

- SES Mock Up (1/2 Car) Plus Engine Components
- TECO Mock Up (Full Car) Plus Engine Components (See Fig. E-4)
- TECO 3/8 Scale Engine Mockup
- Lear Bus (Steam Engine) (Rideable) (See Fig. E-5)
- AERC Organic Turbine System Display

STRATIFIED CHARGE SYSTEMS:

- Chrysler Cricket (Stratified Charge - Static Display)
- Chrysler Stratified Charge Engine Mockup
- Proco Capri
- Postal Vehicle (Proco)

ELECTRIC VEHICLE DISPLAYS:

- ESB Sundancer (Driveable) (All Electric)

GM URBAN: (See Fig. E-6)

- GM ICE/Electric Hybrid (Driveable)
- GM Electric (Driveable)
- GM ICE (Driveable)

EPA Stand Up Display Board

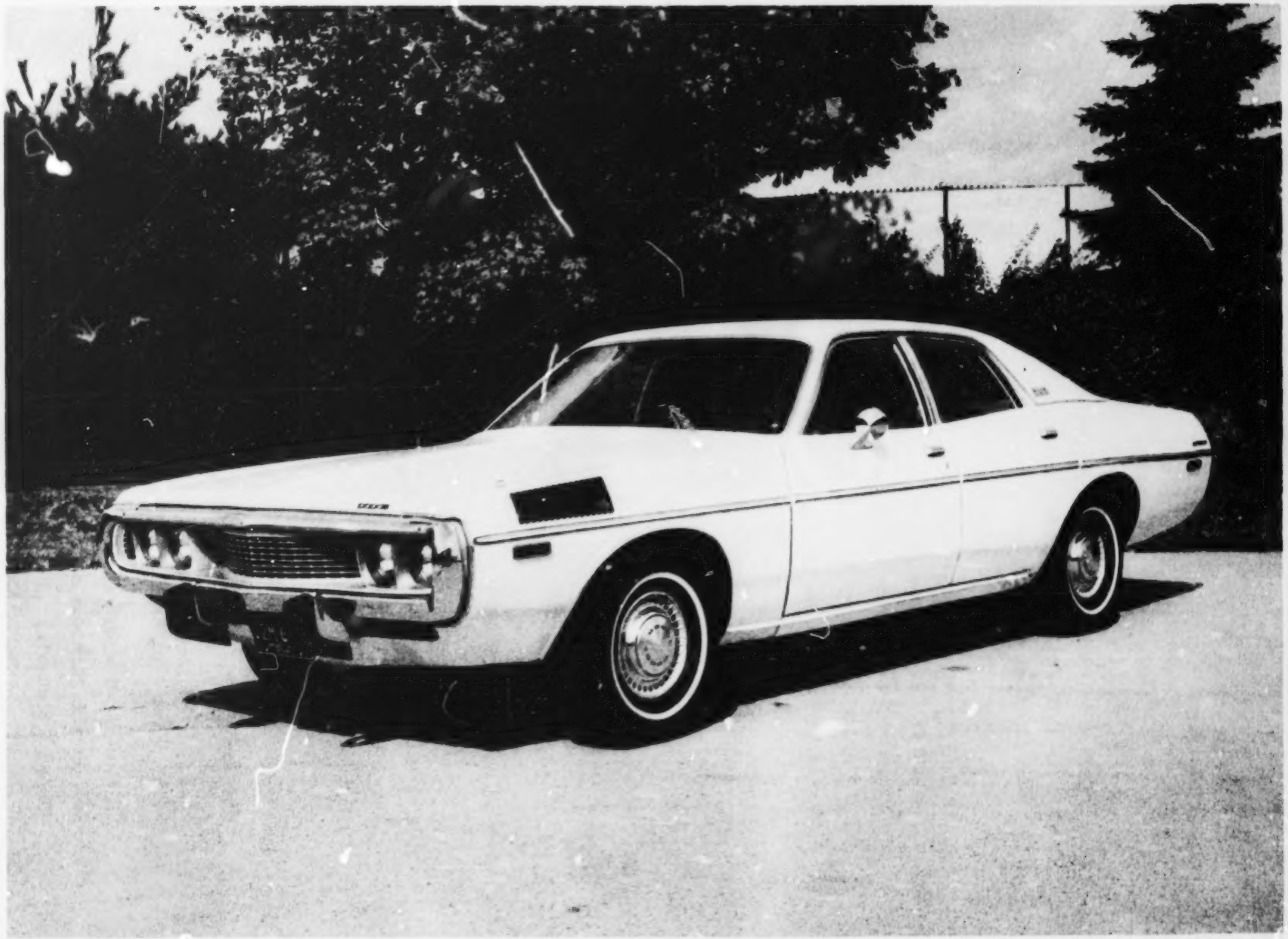

Fig. E-1 Chrysler Gas Turbine Car

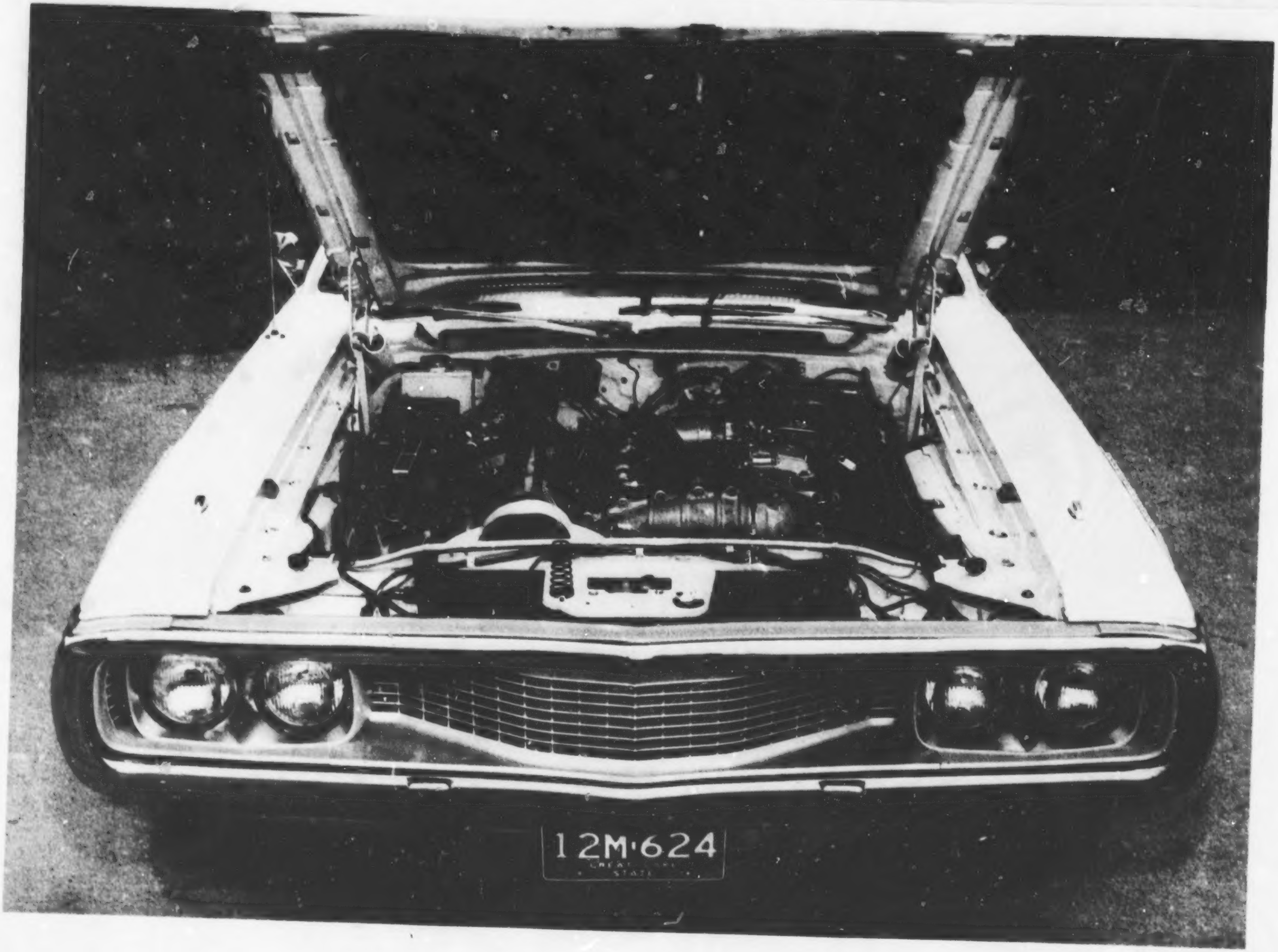

Fig. E-2 Chrysler Gas Turbine Car (Front View)

Fig. E-3 EPA/Williams Research Gas Turbine Car

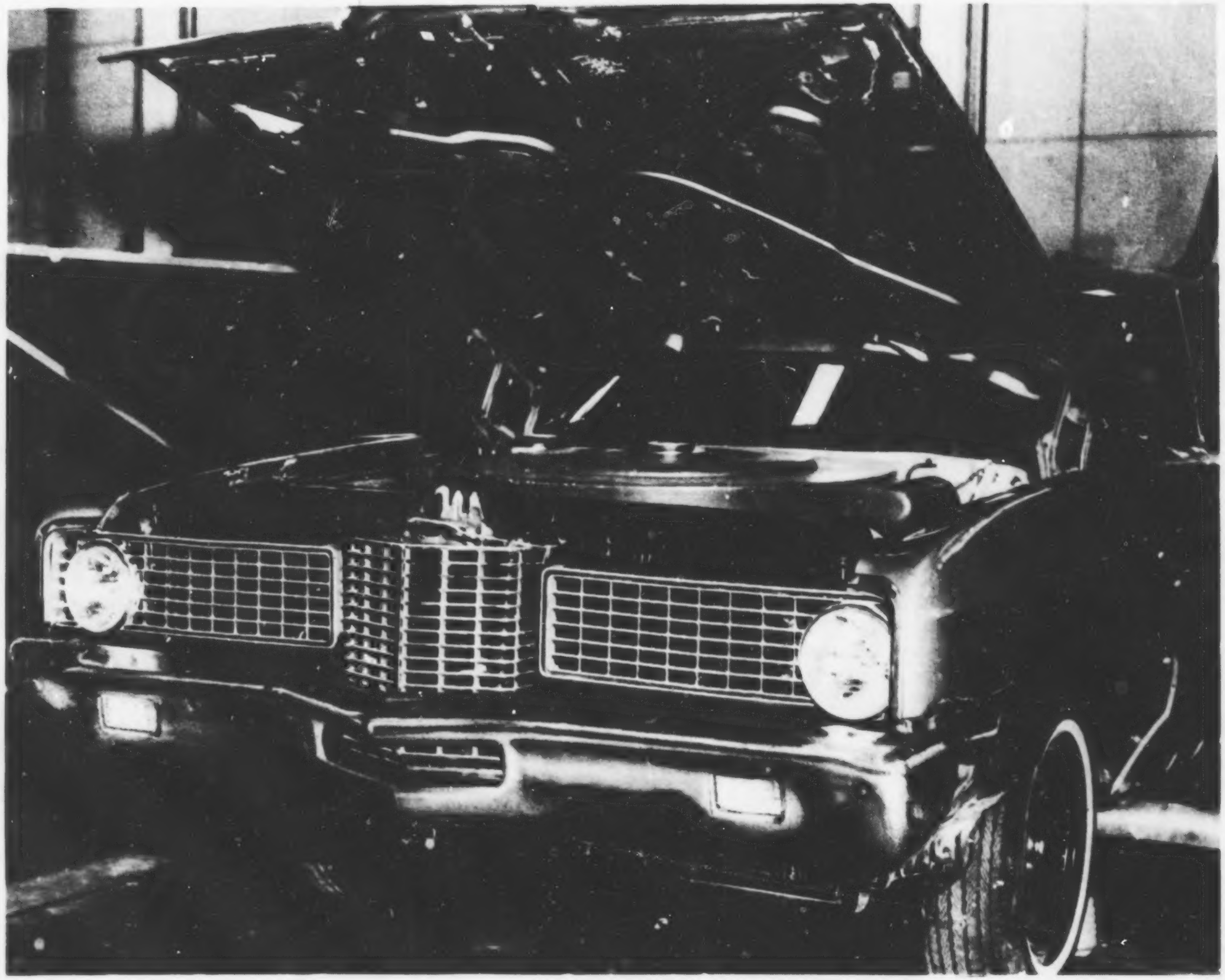

Fig. E-4 Ford Galaxie with Complete Rankine System Mockup Installed

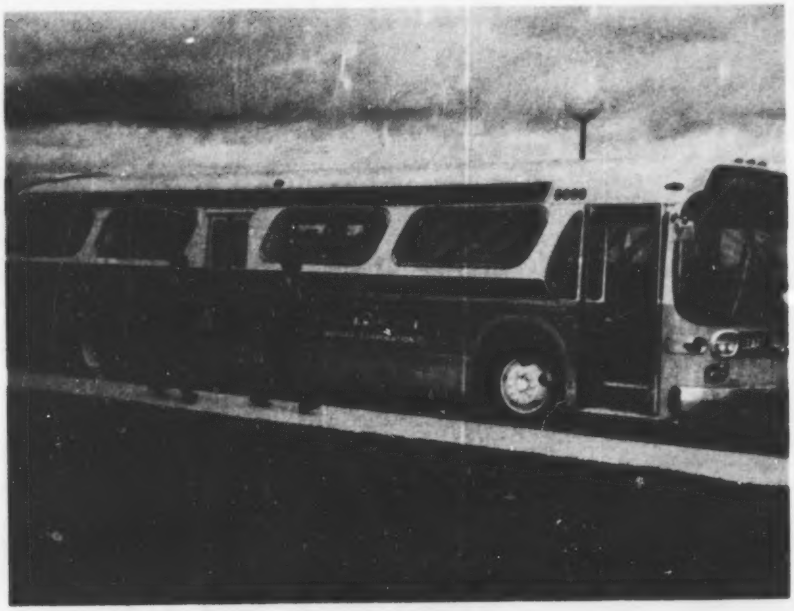

Fig. E-5 Lear Steam Bus

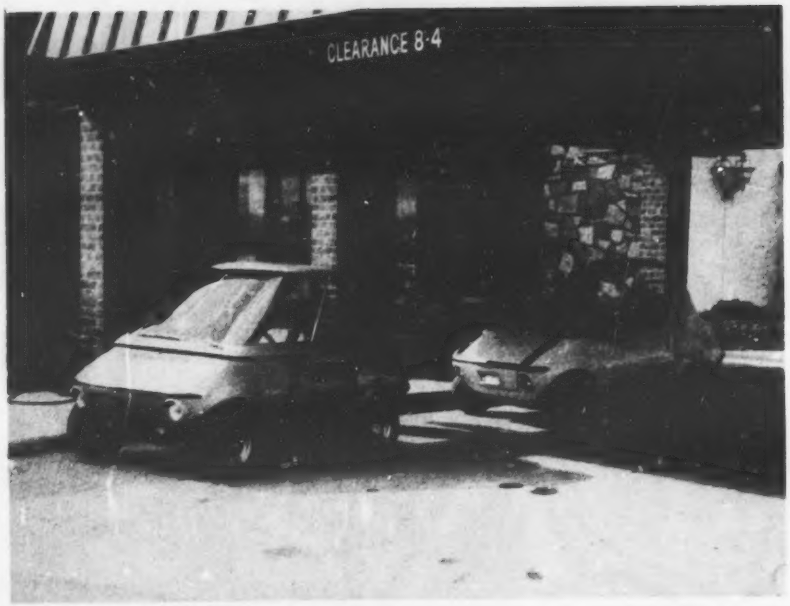
CLEARANCE 8-4

Fig. E-6 Urban Vehicles

APPENDIX E

Bibliography of Alternative Automotive Power Systems Division
Annual, Final, and Summary Reports,
October 1973

BIBLIOGRAPHY OF ALTERNATIVE AUTOMOTIVE POWER SYSTEMS DIVISION

ANNUAL, FINAL, AND SUMMARY REPORTS

OCTOBER 1973

The attached list of publications are annual, summary and final reports of work performed under study and development contracts and interagency agreements funded by the Alternative Automotive Power Systems (AAPS) Program of the Office of Air and Water Programs (OAWP) of the U. S. Environmental Protection Agency.

The Air Pollution Technical Data (APTD) Series and Environmental Protection Agency (EPA) Series Reports are issued to report technical data of interest to a limited readership.

These reports may be obtained in either paper copy or microfiche format by specifying the NTIS Accession Number and submitting the amount listed (payment must accompany orders) to the National Technical Information Service (NTIS).

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Telephone: (703)321-8543

The absence of an NTIS Accession Number indicates that the report is not presently available for the NTIS. Inquiries regarding future availability may be directed to the AAPS Program Office.

Alternative Automotive Power Systems Division
U.S. Environmental Protection Agency
2929 Plymouth Road
Ann Arbor, Michigan 48105
Telephone (313)761-5230 Ext. 296

Federal employees, current contractors and grantees, and non-profit organizations may obtain copies of these reports, free of charge, as supplies permit, by requesting the publication number (APTD Series or EPA Series) from the Air Pollution Technical Information Center (APTIC).

Air Pollution Technical Information Center
U.S. Environmental Protection Agency
Research Triangle Park, North Carolina 27711
Telephone: (919)549-2573

INDEX

RANKINE CYCLE POWER SYSTEM

APTD - 0573
0574
0707
0959
0960
0961
0980
1154
1155
1357
1358
1516
1517
1545
1554
1558
1563
1564
1565
1566
EPA-460/3-73-001

STRATIFIED CHARGE ENGINE

APTD - 1356

BRAYTON CYCLE POWER SYSTEM

APTD - 0958
1226
1290
1291
1343
1359
1374
1441
1454
1457
1517
1546
1558
EPA-460/9-73-001

MODELS

APTD - 0960
0961
0966

HEAT ENGINE/ FLYWHEEL HYBRID

APTD - 0750
1121
1181
1182
1344
1468

HEAT ENGINE/ BATTERY HYBRID

APTD - 0724
0725
0762
0957
1346
1355
1468

BATTERY DEVELOPMENT

APTD - 0875
1126
1345

APPENDIX

RELATED REPORTS

APTD SERIES REPORTS

APTD - 0573
REPORT DATE: June 1970
CONTRACT NUMBER: CPA 22-69-132
CONTRACTOR: Thermo Electron Corporation
REPORT TITLE: "Conceptual Design Rankine Cycle Power System With Organic Working Fluid and Reciprocating Engine for Passenger Vehicles."
NTIS ACCESSION NUMBER: PB 193-418
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 0574
REPORT DATE: June 1970
CONTRACT NUMBER: CPA 22-69-128
CONTRACTOR: The Marquardt Corporation
REPORT TITLE: "Study of Continuous Flow Combustion Systems for External Combustion Vehicle Powerplants."
NTIS ACCESSION NUMBER: PB 193-417
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 0707
REPORT DATE: Undated
CONTRACT NUMBER: EHS 70-106
CONTRACTOR: Solar
REPORT TITLE: "Low Emission Burner for Rankine Cycle Engines for Automobiles."
NTIS ACCESSION NUMBER: PB 202-196
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 0724
REPORT DATE: June 1, 1971
CONTRACT NUMBER: FO 4701-70-C-0059
CONTRACTOR: The Aerospace Corporation
REPORT TITLE: "Hybrid Heat Engine/Electric Systems Study." (Volume I)
NTIS ACCESSION NUMBER: PB 201-645
NTIS PAPER COPY PRICE: $6.00
NTIS MICROFICHE PRICE: $1.45

APTD - 0725
REPORT DATE: June 1, 1971
CONTRACT NUMBER: FO 4701-70-C-0059
CONTRACTOR: The Aerospace Corporation
REPORT TITLE: "Hybrid Heat Engine/Electric Systems Study." (Volume II)
NTIS ACCESSION NUMBER: PB 201-646
NTIS PAPER COPY PRICE: $6.00
NTIS MICROFICHE PRICE: $1.45

APTD -0750
REPORT DATE: April 30, 1971
CONTRACT NUMBER: EHS 70-104
CONTRACTOR: Lockheed Missiles and Space Company
REPORT TITLE: "Flywheel Feasibility Study and Demonstration."
NTIS ACCESSION NUMBER: PB 200-143
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 0762
REPORT DATE: April 1971
CONTRACT NUMBER: EHSH 71-002
CONTRACTOR: TRW Systems Group
REPORT TITLE: "Analysis and Advanced Design Study of an Electromechanical Transmission."
NTIS ACCESSION NUMBER: PB 203-463
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 0875
REPORT DATE: July 1971 (Annual)*
CONTRACT NUMBER: W-31-107-Eng-38
CONTRACTOR: Argonne National Laboratory
REPORT TITLE: "Development of High-Energy Batteries for Electric Vehicles."
NTIS ACCESSION NUMBER: PB 205-254
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 0957
REPORT DATE: January 28, 1971
CONTRACT NUMBER: EHS 70-107
CONTRACTOR: Minicars, Inc.
REPORT TITLE: "Emission Optimization of Heat Engine/Electric Vehicle."
NTIS ACCESSION NUMBER: PB 198-093
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 0958
REPORT DATE: August 1971
CONTRACT NUMBER: EHS 70-115
CONTRACTOR: United Aircraft Research Laboratories
REPORT TITLE: "Manufacturing Cost Study of Selected Gas Turbine Automobile Engine Concepts"
NTIS ACCESSION NUMBER: PB 202-251
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 0959
REPORT DATE: August 1971
CONTRACT NUMBER: EHS 70-123
CONTRACTOR: AiResearch Manufacturing Company
REPORT TITLE: "Compact Condenser for Rankine Cycle Engines."
NTIS ACCESSION NUMBER: PB 208-237
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 0960
REPORT DATE: February 1972
CONTRACT NUMBER: EHS 70-111
CONTRACTOR: General Electric Company
REPORT TITLE: "Modeling, Analysis, and Evaluation of Rankine Cycle Propulsion Systems." (Volume I).
NTIS ACCESSION NUMBER: PB 209-277
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 0961
REPORT DATE: February 1972
CONTRACT NUMBER: EHS 70-111
CONTRACTOR: General Electric Company
REPORT TITLE: "Modeling, Analysis, and Evaluation of Rankine Cycle Propulsion Systems." (Volume II).
NTIS ACCESSION NUMBER: PB 209-278
NTIS PAPER COPY PRICE: $6.00
NTIS MICROFICHE PRICE: $1.45

APTD - 0966
REPORT DATE: October 1971
CONTRACT NUMBER: F19628-71-C-0002
CONTRACTOR: The Mitre Corporation
REPORT TITLE: "Advanced Automotive Power Systems Structured Value Analysis Model."
NTIS ACCESSION NUMBER: PB 209-286
NTIS PAPER COPY PRICE: $6.75**
NTIS MICROFICHE PRICE: $1.45

*NOTE: See APTD-1126 for July 1970 Annual Report.

**Paper copy not presently available from NTIS.

APTD - 0980
REPORT DATE: July 1971
CONTRACT NUMBER: EHS 70-125
CONTRACTOR: Paxve, Inc.
REPORT TITLE: "Evaluation of a Low NO_x Burner."
NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
NTIS MICROFICHE PRICE:

APTD - 1121
REPORT DATE: February 25, 1972
CONTRACT NUMBER: 68-04-0034
CONTRACTOR: Sundstrand Aviation
REPORT TITLE: "Hybrid Propulsion System Transmission Evaluation."
NTIS ACCESSION NUMBER: PB 210-057
NTIS PAPER COPY PRICE: $6.00
NTIS MICROFICHE PRICE: $1.45

APTD - 1126
REPORT DATE: July 1970 (Annual)*
CONTRACT NUMBER: W-31-107-Eng-38
CONTRACTOR: Argonne National Laboratory
REPORT TITLE: "Development of High-Energy Batteries for Electric Vehicles."
NTIS ACCESSION NUMBER: PB 197-576
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 1154
REPORT DATE: May 5, 1972
CONTRACT NUMBER: EHS 70-102
CONTRACTOR: Thermo Electron Corporation
REPORT TITLE: "Detailed Design Rankine-Cycle Power System With Organic-Based Working Fluid and Reciprocating Expander for Automobile Propulsion" (Volume I - Technical Report).
NTIS ACCESSION NUMBER: PB 210-836
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 1155
REPORT DATE: May 5, 1972
CONTRACT NUMBER: EHS 70-102
CONTRACTOR: Thermo Electron Corporation
REPORT TITLE: "Detailed Design Rankine-Cycle Power System With Organic-Based Working Fluid and Reciprocating Expander for Automobile Propulsion" (Volume II - Appendices).
NTIS ACCESSION NUMBER: PB 210-837
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 1181
REPORT DATE: November 1971
CONTRACT NUMBER: 68-04-0033
CONTRACTOR: Mechanical Technology Incorporated
REPORT TITLE: "Feasibility Analysis of the Transmission for a Flywheel/Heat Engine Hybrid Propulsion System."
NTIS ACCESSION NUMBER: PB 212-097
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 1182
REPORT DATE: July 31, 1972
CONTRACT NUMBER: 68-04-0048
CONTRACTOR: Lockheed Missiles and Space Company, Inc.
REPORT TITLE: "Flywheel Drive Systems Study."
NTIS ACCESSION NUMBER: PB 213-342
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

*NOTE: See APTD-0875 for July 1971 Annual Report

APTD - 1226 NTIS ACCESSION NUMBER: PB 220-148
REPORT DATE: August 1972 NTIS PAPER COPY PRICE: $6.00
CONTRACT NUMBER: EHSH 71-003 NTIS MICROFICHE PRICE: $1.45
CONTRACTOR: Thermo Mechanical Systems Company
REPORT TITLE: "The Study of Low Emission Vehicle Power Plants Using Gaseous Working Fluids."

APTD - 1290 NTIS ACCESSION NUMBER:
REPORT DATE: May 1972 NTIS PAPER COPY PRICE:
CONTRACT NUMBER: 68-04-0013 NTIS MICROFICHE PRICE:
CONTRACTOR: United Aircraft Research Laboratories
REPORT TITLE: "Automotive Gas Turbine Optimum Configuration Study."

APTD - 1291* NTIS ACCESSION NUMBER: PB 213-389
REPORT DATE: July 14, 1972 NTIS PAPER COPY PRICE: $6.00
CONTRACT NUMBER: 68-04-0012 NTIS MICROFICHE PRICE: $1.45
CONTRACTOR: AiResearch Manufacturing Company
REPORT TITLE: "Automobile Gas Turbine Optimization Study"

APTD - 1343 NTIS ACCESSION NUMBER: PB 213-370
REPORT DATE: June 1972 NTIS PAPER COPY PRICE: $6.00
CONTRACT NUMBER: 68-01-0406 NTIS MICROFICHE PRICE: $1.45
CONTRACTOR: General Electric Company
REPORT TITLE: "Automobile Gas Turbine - Optimum Cycle Selection Study."

APTD - 1344 NTIS ACCESSION NUMBER: PB 213-417
REPORT DATE: March 1972 NTIS PAPER COPY PRICE: $6.75
CONTRACT NUMBER: N00017-62-C-0604 NTIS MICROFICHE PRICE: $1.45
CONTRACTOR: John Hopkins University - Applied Physics Laboratory
REPORT TITLE: "Heat-Engine/Mechanical-Energy-Storage Hybrid Propulsion Systems for Vehicles."

APTD - 1345 NTIS ACCESSION NUMBER: PB 213-257
REPORT DATE: April 1972 NTIS PAPER COPY PRICE: $3.00
CONTRACT NUMBER: 68-04-0028 NTIS MICROFICHE PRICE: $1.45
CONTRACTOR: TRW Systems Group
REPORT TITLE: "Develop High Charge and Discharge Rate Lead/Acid Battery Technology."

APTD - 1346 NTIS ACCESSION NUMBER:
REPORT DATE: November 1971 NTIS PAPER COPY PRICE:
CONTRACT NUMBER: EHSH 71-009 NTIS MICROFICHE PRICE:
CONTRACTOR: Tyco Laboratories, Incorporated
REPORT TITLE: "Lead/Acid Battery Development for Heat Engine/Electric Hybrid Vehicles."

*NOTE: APTD-1546 is a Summary of This Report.

APTD - 1355
REPORT DATE: April 1972
CONTRACT NUMBER: 68-04-0058
CONTRACTOR: TRW Systems Group
REPORT TITLE: "Cost and Emission Studies of a Heat Engine/Battery Hybrid Family Car."
NTIS ACCESSION NUMBER: PB 213-280
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 1356
REPORT DATE: January 31, 1972
CONTRACT NUMBER: 68-04-0040 (Phase II)
CONTRACTOR: Cornell Aeronautical Laboratory
REPORT TITLE: "The Evaluation of the Stratified Charge Engine (SCE) Concept."
NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
NTIS MICROFICHE PRICE:

APTD - 1357
REPORT DATE: December 1972
CONTRACT NUMBER: 68-01-0430
CONTRACTOR: Chandler Evans
REPORT TITLE: "Vapor Generator Feed Pump for Rankine Cycle Automotive Propulsion System (Chandler Evans)."
NTIS ACCESSION NUMBER: PB 222-849
NTIS PAPER COPY PRICE: $5.50
NTIS MICROFICHE PRICE: $1.45

APTD - 1358
REPORT DATE: December 1972
CONTRACT NUMBER: 68-01-0437
CONTRACTOR: Lear Motors Corporation
REPORT TITLE: "Vapor Generator Feed Pump for Rankine Cycle Automotive Propulsion System."
NTIS ACCESSION NUMBER: PB 222-871
NTIS PAPER COPY PRICE: $3.50
NTIS MICROFICHE PRICE: $1.45

APTD - 1359*
REPORT DATE: December 1972
CONTRACT NUMBER: 68-01-0405
CONTRACTOR: Williams Research Corporation
REPORT TITLE: "Automotive Gas Turbine Economic Analysis."
NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
NTIS MICROFICHE PRICE:

APTD - 1374
REPORT DATE: February 1973
CONTRACT NUMBER: 68-04-0014
CONTRACTOR: AiResearch Manufacturing Company of Arizona
REPORT TITLE: "Low NOx Emission Combustor Study for Automobile Gas Turbine Engines."
NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
NTIS MICROFICHE PRICE:

APTD - 1441
REPORT DATE: February 1973
CONTRACT NUMBER: 68-04-0016
CONTRACTOR: Solar Division, International Harvester Company
REPORT TITLE: "Low NOx Emission Combustor for Automobile Gas Turbine Engines."
NTIS ACCESSION NUMBER: PB 222-818
NTIS PAPER COPY PRICE: $7.25
NTIS MICROFICHE PRICE: $1.45

* NOTE: See Supplement Report EPA-460/9-73-001

APTD - 1454 NTIS ACCESSION NUMBER: PB 222-340
REPORT DATE: February 1973 NTIS PAPER COPY PRICE: $11.25
CONTRACT NUMBER: 68-04-0017 NTIS MICROFICHE PRICE: $1.45
CONTRACTOR: Northern Research and Engineering Corporation
REPORT TITLE: "Low NOx Emission Combustor for Automobile Gas Turbine Engines (Northern Research and Engineering Corporation)."

APTD - 1457 NTIS ACCESSION NUMBER: PB 222-075
REPORT DATE: February 1973 NTIS PAPER COPY PRICE: $6.75
CONTRACT NUMBER: 68-04-0015 NTIS MICROFICHE PRICE: $1.45
CONTRACTOR: United Aircraft of Canada Limited
REPORT TITLE: "Low NOx Emission Combustor for Automobile Gas Turbine Engines."

APTD - 1468 NTIS ACCESSION NUMBER:
REPORT DATE: March 1972 NTIS PAPER COPY PRICE:
CONTRACT NUMBER: Interagency NTIS MICROFICHE PRICE:
CONTRACTOR: Bureau of Mines
REPORT TITLE: "Emission Characteristics of Spark Ignition Internal Combustion Engines Used as the Prime Mover in a Hybrid System."

APTD - 1516 NTIS ACCESSION NUMBER:
REPORT DATE: April 1973 NTIS PAPER COPY PRICE:
CONTRACT NUMBER: EHS 70-117 NTIS MICROFICHE PRICE:
CONTRACTOR: Battelle Columbus Laboratories
REPORT TITLE: "Low Emission Burners for Automotive Rankine Cycle Engines."

APTD - 1517 NTIS ACCESSION NUMBER:
REPORT DATE: May 1973 NTIS PAPER COPY PRICE:
CONTRACT NUMBER: 68-04-0033 NTIS MICROFICHE PRICE:
CONTRACTOR: Mechanical Technology Incorporated
REPORT TITLE: "Transmission for Advanced Automotive Single-Shaft Gas Turbine and Turbo-Rankine Engine."

APTD - 1545 NTIS ACCESSION NUMBER: PB 222-349
REPORT DATE: July 1972 NTIS PAPER COPY PRICE: $11.25
PRIME CONTRACT NUMBER: 68-04-0004 NTIS MICROFICHE PRICE: $1.45
PRIME CONTRACTOR: Steam Engine Systems Corporation
SUB CONTRACTOR: The Bendix Corporation
REPORT TITLE: "Steam Car Control Analysis."

APTD - 1546
REPORT DATE: September 15, 1972
CONTRACT NUMBER: 68-04-0012
CONTRACTOR: AiResearch Manufacturing Company of Arizona
REPORT TITLE: "Automobile Gas Turbine Engine Study"
NOTE: This is a summary report of APTD-1291.
NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
NTIS MICROFICHE PRICE:

APTD - 1554 *
REPORT DATE: June, 1973
CONTRACT NUMBER: 68-04-0019
CONTRACTOR: University of Michigan
REPORT TITLE: "Heat Transfer and Flow Friction Performance of Heated Perforated Flat Plates"
NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
NTIS MICROFICHE PRICE:

APTD - 1558 *
REPORT DATE: December 15, 1972
CONTRACT NUMBER: 68-04-0034
CONTRACTOR: Sunstrand
REPORT TITLE: "Transmission Study for Turbine and Rankine Cycle Engines"
NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
NTIS MICROFICHE PRICE:

APTD - 1563
REPORT DATE: June 1973
CONTRACT NUMBER: 68-04-0030
CONTRACTOR: Monsanto Research Corporation
REPORT TITLE: "Optimum Working Fluids for Automotive Rankine Engines, Volume I - Executive Summary"
NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
NTIS MICROFICHE PRICE:

APTD - 1564
REPORT DATE: June 1973
CONTRACT NUMBER: 68-04-0030
CONTRACTOR: Monsanto Research Corporation
REPORT TITLE: "Optimum Working Fluids for Automotive Rankine Engines, Volum3 II - Technical Section"
NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
NTIS MICROFICHE PRICE:

APTD - 1565
REPORT DATE: June 1973
CONTRACT NUMBER: 68-04-0030
CONTRACTOR: Monsanto Research Corporation
REPORT TITLE: "Optimum Working Fluids for Automotive Rankine Engines, Volume III - Technical Section - Appendices"
NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
NTIS MICROFICHE PRICE:

APTD - 1566
REPORT DATE: June 1973
CONTRACT NUMBER: 68-04-0030
CONTRACTOR: Monsanto Research Corporation
REPORT TITLE: "Optimum Working Fluids for Automotive Rankine Engines, Volume IV - Engine Design Optimization"
NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
NTIS MICROFICHE PRICE:

* Publication Pending

EPA SERIES REPORTS

EPA - 460/9-73-001* NTIS ACCESSION NUMBER:
REPORT DATE: July 1973 NTIS PAPER COPY PRICE:
CONTRACT NUMBER: 68-01-0405 NTIS MICROFICHE PRICE:
CONTRACTOR: Williams Research Corporation
REPORT TITLE: "Automotive Gas Turbine Economic Analysis, Investment Cast Turbine Wheel Supplement"
NOTE: This is a supplement to APTD - 1359.

EPA - 460/3-73-001* NTIS ACCESSION NUMBER:
REPORT DATE: September 1973 NTIS PAPER COPY PRICE:
CONTRACT NUMBER: 68-01-0461 NTIS MICROFICHE PRICE:
CONTRACTOR: General Electric Company
REPORT TITLE: "Development of Low Emission Porous-Plate Combustor for Automotive Gas Turbine and Rankine Cycle Engines"

EPA - 460/3-73-003* NTIS ACCESSION NUMBER:
REPORT DATE: October 1973 NTIS PAPER COPY PRICE:
CONTRACT NUMBER: 68-01-0408 NTIS MICROFICHE PRICE:
CONTRACTOR: General Electric Company
REPORT TITLE: "Final Report, Design of Reciprocating Single Cylinder Expanders for Steam".

EPA - 460/3-73-004* NTIS ACCESSION NUMBER:
REPORT DATE: October 1973 NTIS PAPER COPY PRICE:
CONTRACT NUMBER: 68-04-0036 NTIS MICROFICHE PRICE:
CONTRACTOR: Solar Division International Harvester Company
REPORT TITLE: "Low Emission Combustor/Vapor Generator for Automobile Rankine Cycle Engines".

* Publication Pending

REPORTS RELATED TO THE AAPS PROGRAM

APTD - 69-51
REPORT DATE: October 1969
CONTRACT NUMBER: PH 86-67-109
CONTRACTOR: Battelle Memorial Institute
REPORT TITLE: "Study of Unconventional Thermal, Mechanical, and Nuclear Low-Pollution-Potential Power Sources for Urban Vehicles."
NTIS ACCESSION NUMBER: PB 192-321
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 69-52
REPORT DATE: October 1969
CONTRACT NUMBER: PH 86-67-108
CONTRACTOR: Arthur D. Little, Inc.
REPORT TITLE: "Prospects for Electric Vehicles, A Study of Low-Pollution-Potential Vehicles - Electric."
NTIS ACCESSION NUMBER: PB 194-814
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APPENDIX F

Status Report on Hazards of Nickel Oxide

October 12, 1973

Status Report on Hazards of Nickel Oxide

October 12, 1973

Background: This is a short status report on the EPA/AAPSD investigation to determine the potential carcinogenic hazard from automotive gas turbine engine exhaust of nickel oxide regenerator rubbing seal material. It was found by analysis that the nickel exhaust from an automotive gas turbine engine due to wear of state-of-the-art nickel oxide (NiO) and calcium fluoride (CaF_2) rubbing seals could result in engine exhaust particulate levels of the same order as the current Threshold Limit Value (TLV) for nickel of 1,000 microgram per cubic meter ($\mu g/m^3$) in the air.

The EPA Pathobiology Research Branch surveyed the toxicologic literature on the carcinogenicity of NiO. The principal concerns found over the release of additional NiO to the atmosphere were as follows:

1. The compound produces muscel sarcomas when injected into rats.
2. Nickel oxide may function as a cocarcinogen when introduced into the lungs with a known carcinogen.
3. Low level (100-150 $\mu g/m^3$) nickel oxide exposure may result in histological changes in bronchi and alveoli.
4. Nickel oxide is cleared relatively slowly from the respiratory tract.
5. Cigarette smoking may impair clearance of nickel oxide and potentiate tissue damage.
6. Nickel oxide has been implicated by association in the higher incidence of nasal and lung cancer observed among nickel workers.

Progress: Since the last AAPS Coordination Meeting in June 1973 the exhaust particulates from the Williams Research Corporation gas turbine powered AMC Hornet automobile have been measured at The Dow Chemical Company in

Midland, Michigan. This prototype vehicle is powered by the WR-26 gas turbine engine which utilizes two ceramic disc regenerators. The flame sprayed regenerator rubbing seal material composition is 90 percent NiO and 10 percent CaF_2. A summary of the measured total particulates and trace nickel is given in the following table:

Vehicle Test No.	Test Procedure	Particulate (gram/mile) Total	NiO
260A	FDC* Cold Start	0.68	.0034
B	FDC Hot Start	0.29	.0025
C	FDC Hot Start	0.27	.0020
D	50 mph Steady State	0.14	.0005

*1975 Federal Driving Cycle

The total particulates reported in the table were collected with a millipore filter. The NiO emissions rate was determined from the percent nickel from emission spectroscope analysis of the total particulate and assumes all NiO.

Planned Action: The next major task planned is to relate the NiO emission from gas turbine vehicles in grams/mile to ambient air concentrations. An analysis will be made of the likely increase in urban ambient levels of nickel resulting from a projected number of gas turbine automobiles with NiO seals. It is planned to have this analysis performed by the EPA Monitoring and Data Analysis Division, Source Receptor Analysis Branch.

Conclusion: Our NiO investigation has not been completed. The NiO emission levels from automotive gas turbines are low enough so that it is difficult to make a firm conclusion about the health hazard without completing the analysis relating vehicle grams per mile of exhaust NiO to ambient nickel levels. Until EPA sets ambient air quality standards for nickel, the AAPSD recommendation on acceptable NiO engine exhaust will be based on not increasing the urban ambient levels of nickel by introducing large numbers of automobiles powered by gas turbine engines with NiO seals. In the meantime it is suggested that the material be handled with extreme caution, and that alternative regenerator seal materials be at least considered.

If you want more detailed references and discussion on the NiO investigation as completed to date, or would like to discuss the subject, please contact Robert Schulz (Tel: 313-761-5230, ext. 320).

APPENDIX G

Summary of Exhaust Emission Test Procedures and Standards

APPENDIX I

EXHAUST EMISSION TEST PROCEDURES

1968 Federal Test Procedure (FTP) - Fed. Reg. Vol. 33 No. 108 (6/1/68)

- Cold start followed by 137-second cycle repeated 7 times for a total of 6 miles
- Emission concentrations measured continuously and data from specific portions of the test weighted.
- Result expressed as concentrations.

1972 Mass Emissions Procedure (CVS-72) - Fed. Reg. Vol. 36 No. 55 (3/20/71)

- Cold start followed by 7.5 mile simulated urban trip.
- Proportional mass sample of exhaust collected in a bag throughout test and emission concentrations in bag measured after test
- Result expressed as grams per mile.

1975 Mass Emissions Procedure (CVS-75) - Fed. Reg. Vol. 36 No. 128 (7/2/71)

- Cold start followed by 7.5 mile simulated urban trip, consisting of 3.6 mile warm up trip (Bag 2) and 3.9 mile hot trip (Bag B)
- Car stopped and allowed to stand for ten minutes.
- Car restarted and 3.6 mile warm-up trip repeated (Bag C).
- Proportional mass samples of exhaust collected in three bags and emission concentrations in bags measured after test.
- Weighted emissions = 43% Bag A + 100% Bag B + 57% Bag C.
- Result expressed as grams per mile.

ESTIMATED EXHAUST EMISSIONS PRIOR TO EMISSION STANDARDS

(EXPRESSED IN GRAMS PER MILE)

Exhaust Emission Test Procedure	Exhaust Emission		
	HC	CO	NOx
FTP	(11.0)	(80.0)	(4-6)
CVS-72	(9.5)	(98.0)	(3.4)
CVS-75	(8.6)	(87.5)	(3.5)

EVAPORATIVE EMISSIONS STANDARDS

(Evaporative Emissions Expressed in Grams per Test)

YEAR	EVAPORATIVE HC EMISSION
Prior to 1971	No Standard
1971	6.0
1972 - 1977	2.0

AUTOMOBILE EXHAUST EMISSION STANDARDS (1966-1971)

(HC Concentrations Expressed in Parts per Million)
(CO Concentrations Expressed in Percent)
(NOx Standard Not Applicable)

	FEDERAL EXHAUST EMISSION STANDARD		CALIFORNIA EXHAUST EMISSION STANDARD		
YEAR(S)	HC (ppm)	CO (%)	HC (ppm)	CO (%)	CID
1966 - 1967	No Standard		410 350 275	2.3 2.0 1.5	50-100 101-140 Over 140
1968 - 1969	275	1.5			
1970 - 1971	180	1.0	180	1.0	ALL

AUTOMOBILE EXHAUST EMISSION STANDARDS (1966 - 1977)

(EXPRESSED IN GRAMS PER MILE)

APPLICABLE YEAR(S)	EXHAUST EMISSION TEST PROCEDURE	FEDERAL EXHAUST EMISSION STANDARDS			CALIFORNIA EXHAUST EMISSION STANDARDS		
		HC	CO	NOX	HC	CO	NOX
1966 - 1967	FTP	*	*	*	(3.4)	(35.0)	*
1968 - 1969	FTP	(3.4)	(35.0)	*	(3.4)	(35.0)	*
1970	FTP	(2.2)	(23.0)	*	(2.2)	(23.0)	*
1971	FTP	(2.2)	(23.0)	*	(2.2)	(23.0)	(4.0)
1971	CVS - 72	(4.6)	(47.0)	*			
1972	CVS - 72	3.4	39.0	*	3.4	39.0	3.2
1973	CVS - 72	3.4	39.0	3.0	3.4	39.0	3.2
1974	CVS - 72	3.4	39.0	3.0	3.4	39.0	2.0
1975 Original	CVS - 75	0.41	3.4	3.0	1.0	24.0	1.5
1975 Interim	CVS - 75	1.5	15.0	3.1	0.9	9.0	2.0
1976 Original	CVS - 75	0.41	3.4	0.4	0.41	3.4	0.4
1976 Interim	CVS - 75	0.41	3.4	2.0			
1977	CVS - 75	0.41	3.4	0.4			

* No standard was applicable

( )Numbers in parentheses are not standards but are estimates of average emission levels, in grams per mile, had the indicated test procedure been used.